

IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

<p>NORTHEAST CONTROLS, INC. and ST. PAUL MERCURY INSURANCE COMPANY</p> <p style="text-align: center;">Plaintiffs,</p> <p style="text-align: center;">v.</p> <p>FISHER CONTROLS INTERNATIONAL, LLC</p> <p style="text-align: center;">Defendant.</p>	<p style="text-align: center;">NO. 06-412</p> <p style="text-align: center;">AFFIDAVIT OF DANIEL J. GUNTER IN SUPPORT OF DEFENDANT FISHER'S REPLY BRIEF IN SUPPORT OF ITS MOTION FOR SUMMARY JUDGMENT</p>
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STATE OF WASHINGTON)
: ss.
County of King)

I, DANIEL J. GUNTER, being duly sworn, depose and state as follows:

1. I am one of the attorneys representing defendant Fisher Controls International, LLC ("Fisher"), in the above matter. I was also one of the attorneys representing Fisher in the four underlying actions. I am competent to attest as to the matters set forth herein, and I make this affidavit based on my personal knowledge.

2. Attached hereto as Exhibit 62 is a true and correct copy of Newton, B.E., and Forsythe, E.T., "Cause and Origin Analyses of Two Large Industrial Oxygen Valve Fires," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Tenth Volume*, ASTM STP 1454 (2003).

3. Attached hereto as Exhibit 63 is a true and correct copy of Praxair Standard EN-6 on Maximum Allowable Velocities of Gaseous Oxygen in Piping and Piping Components. This standard was produced in the underlying actions and introduced as an exhibit for the deposition

of Bhim Bhakoo taken in the underlying actions.

4. Attached hereto as Exhibit 64 is a true and correct copy of the ASTM G 94 - 92 Standard Guide for Evaluating Metals for Oxygen service published by the ASTM Committee G-4 on Compatibility and Sensitivity of Materials in Oxygen Enriched Atmosphere.

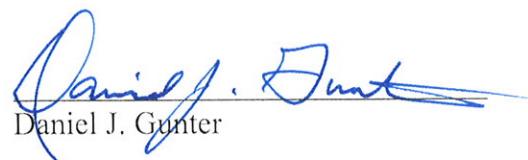
5. Attached hereto as Exhibit 65 is a true and correct copy of selected pages of the deposition testimony of Albert Cappellini taken in this action.

6. Attached hereto as Exhibit 66 is a true and correct copy of selected pages of the deposition testimony of Michael J. Peters taken in this action.

7. Attached hereto as Exhibit 67 is a true and correct copy of selected pages of the deposition testimony of David B. Pope taken in this action.

8. Attached hereto as Exhibit 68 is a true and correct copy of selected pages of the deposition testimony of Bhim Bhakoo taken in the underlying action.

9. Attached hereto as Exhibit 69 is a true and correct copy of selected pages of the deposition testimony of Bhim Bhakoo taken in this action.



Daniel J. Gunter

Subscribed and sworn to before me this 29th day of November, 2007.



Printed Name: Molly J. McInnis
Notary Public, State of Washington
Residing at Enumclaw
My commission expires: 9/8/2011



EXHIBIT 62

NEWTON AND FORSYTH ON LARGE INDUSTRIAL OXYGEN VALVE FIRES 269

However, on occasion, because of the inherent risk of fire associated with oxygen production and delivery, combined with the present state of the art associated with risk minimization, fires still occur. This paper was prepared in an effort to communicate some conclusions from two recent valve fires and to share some analytical tools used in the forensic investigations that may benefit the industry.

Cause And Origin Analyses Of Two Large Industrial Oxygen Valve Fires

Barry Newton¹ and Elliot T. Forsyth²

REFERENCE: Newton, B. E., and Forsyth, E. T., "Cause And Origin Analyses Of Two Large Industrial Oxygen Valve Fires," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Tenth Volume, ASTM STP 1434*, T. A. Steinberg, H. D. Beeson, and B. E. Newton, Eds., ASTM International, West Conshohocken, PA, 2003.

ABSTRACT: Two recent fires were investigated in industrial gas oxygen delivery systems that resulted in significant facility damage as well as personnel injury and death. One fire developed in a 6-in. ball valve being utilized as an isolation valve. This fire was kindled while the valve was being opened under a low-pressure differential and resulted in extensive burnout and significant facility destruction. The other fire developed in a 12-in. butterfly valve being utilized as a pipeline isolation and pressurization control valve downstream of an oxygen boost compressor. The valve utilized generally good materials but was vulnerable to ignition and sustained propagation probably due to the presence of an unusual kindling chain. This paper reviews the investigations and analytical work performed during the accident reconstructions and highlights the "lessons learned" from the incidents.

KEYWORDS: fire investigation, failure analysis, oxygen fire, cause and origin analysis, pipeline fires, root cause analysis

Foreword

Two recent valve fires in industrial oxygen systems were investigated by Wendell Hull & Associates, Inc. (WHA). The results of these incidents have emphasized the extreme nature of fires in pipeline systems and have underscored several important considerations in the design of industrial oxygen systems.

WHA is a small engineering consulting firm with an internationally recognized expertise in oxygen system fire hazards and safety. WHA has extensive experience consulting with industrial gas producers and consumers. In our experience, the industry is keenly aware of the fire hazards associated with oxygen systems and generally is careful to identify and minimize known hazards. The industry consistently uses tools such as hazards analyses, fire risk assessments, failure modes evaluations, and coordinated industry communications to ensure safe systems and advance oxygen compatibility science while still responding to the demand for higher pressure oxygen, higher throughput production, and cost-effective solutions to the most demanding applications. Further, the industry has aggressively pursued oxygen compatibility testing and materials research in an effort to identify and implement the most compatible, yet practical, engineering materials available.

Valve and Incident Description

During July of 2001 a fire occurred in a 6-in. ball valve being used as a pipeline isolation valve. A cross-sectional view of the valve is shown in Figure 1. The valve had a one-piece stem and ball that rode on low-friction trunnion bearing surfaces (CTFE/phenolic) in the body and bonnet. It was a quarter-turn design, meaning the ball/stem traveled through a 90° rotation from fully closed to fully open. The valve was

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designed with a spring-assisted seat on both the upstream and downstream sides of the ball. The valve body, bonnet, ball, stem, and hard seat were all carbon steel. The seals were primarily Buna-N throughout. The valve had two-seat lubrication injection fittings located external to the upstream and downstream seat assemblies to allow the seat and ball to be lubricated on a periodic maintenance cycle. A hydrocarbon-based general purpose grease was specified for this application. The valve was equipped with a multiple-turn hand wheel actuator that rotated the ball counter-clockwise to open and clockwise to close through approximately 11 turns of the hand wheel.

Just prior to the fire, the valve had been closed and a leak check performed on the valve by bleeding off pressure downstream and monitoring the pressure differential across the valve. During this leak check, system data indicated that the upstream pressure was approximately 550 psig (3.8 MPa) and the downstream pressure was approximately 510 psig (3.5 MPa), or roughly a 40-psig (0.28-MPa) differential pressure. At this point, the valve was to be re-opened to establish flow and provide full system pressure. As the valve was being opened manually by the hand wheel, a fire developed within the valve that consumed most of the valve internals and surrounding valve body, and burned out downstream piping and flanges. The operator was killed in the incident.

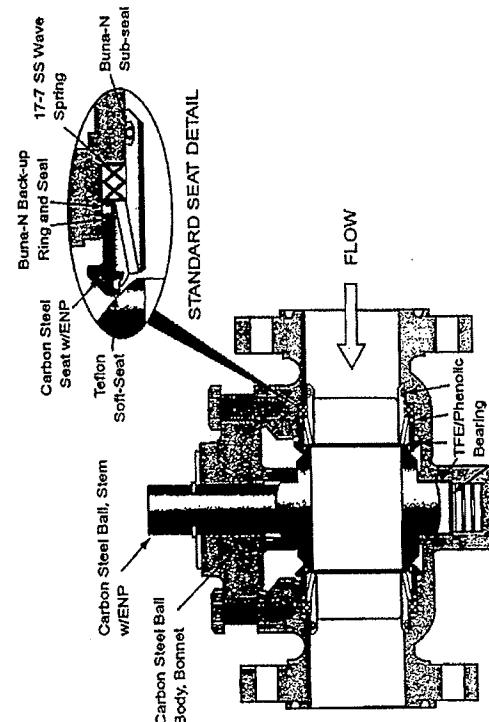


FIG. 1 - 6-in. Ball Valve Used as Isolation Valve in Oxygen Pipeline.

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WHA was requested to investigate the cause and origin of the fire and began by reconstructing the available evidence. An exemplar ball valve to the incident valve was also in the system at the time of the fire (shown in Figure 2). Both the exemplar valve



FIG. 2 - Exemplar valve located upstream of incident valve.

and the incident valve had been in service for approximately 5 years, though they were never actuated (closed) except potentially on one prior occasion. The exemplar valve proved useful to the investigation in many ways, including providing a "clocking" reference for matching the incident valve's actuator position, providing a three-dimensional model of the valve internals to document flow through the valve, and providing samples of materials to identify by chemical analysis, especially lubricants. The valve was also referenced, along with the use of other analytical tools, to reconstruct the burned fragments of the incident valve into their approximate pre-fire positions. Figure 3 depicts the fire-damaged condition of the incident valve after assembling these fragments.

Burn Pattern Observations

Figure 4 depicts a front view of the fire-damaged valve showing the significant level of fire involvement for all internal components of the valve. While the valve exhibited heavy burning from its upstream seat assembly throughout the valve and downstream piping, several significant burn-propagation patterns were still identifiable. These patterns were studied extensively in the cause and origin analysis and some of the major observations are discussed below.

assembly compared to significant burning and evidence of melt-flow extending downstream from this location. These burn patterns suggested an early local origin in the proximity of the upstream seat. This observation is consistent with previous experience indicating that for flowing oxygen systems of primarily metallic components, burn patterns usually do not extend upstream of the local origin of the fire. WHA experience as observed that melt-flow patterns and propagation typically progress in a "fire follows flow" pattern and generally begin to quench once the pressure containment is breached.

[1] A close up view of the segment of fire-damaged valve proximate to where the upstream seat retainer normally resided is shown in Figure 5. All melt-flow patterns emanated from this proximity towards downstream. Fire erosion and melt-flow developed circumferentially around the seat assembly in a highly symmetric pattern. This segment of the valve was the only area where geometrically consistent burning was observed and is thought to have become fully involved in the early stages of the fire while the pressure containment was still intact. As can be seen in Figure 5, no burning extended upstream of this general proximity.



FIG. 3 - Reconstruction of the fire-damaged valve/piping components.

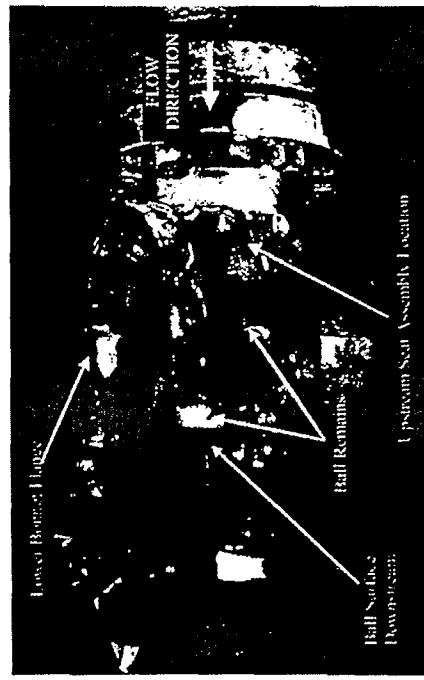


FIG. 4 - Front view of fire-damaged ball valve.

First, it was noteworthy that no burning or melt-flow patterns (i.e., resolidified metal slag showing its flow patterns as a liquid) were observed upstream of the main seat



FIG. 5 - Close-up view of burn patterns near original location of upstream seat retainer.

A second major observation was that burning on the body was heaviest on the backside of the valve (as viewed in Figure 4, side opposite the actuator wheel in Figure 3) and more substantial on the downstream side. The front side of the body also sustained significant damage as only discontinuous segments remained, mostly under the ball and associated with the lower shaft housing. The upper shaft and top of the ball were completely consumed. Only the upper bonnet flange remained intact (connected to the actuator, as shown in Figure 3), but it was heavily lanced during the event.

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A third major observation from burn patterns was that the recovered ball fragment shows a strong preference for burning from upstream to downstream. It was considered significant that the upstream side of the ball element was heavily melted and burned, probably kindled from the burning upstream seat assembly, but the inside and outside diameters of the ball on the downstream side were relatively free of both slag or fire erosion. Figure 6 shows a top view of the fire-damaged ball and upstream seat retainer housing. The top of the ball and upper shaft sustained severe burning, separating the shaft below its extension up through the bonnet and into the actuator.¹ The differences in burning between the upstream and downstream sides of the ball element were considered significant.

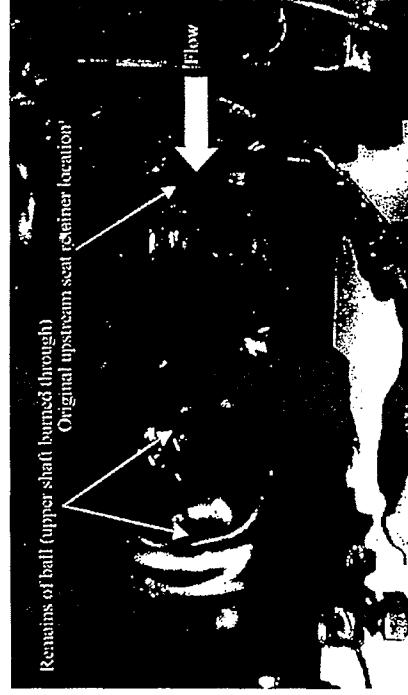


FIG. 6 – Top view of burn patterns on ball and original upstream seat retainer location.

The downstream ball segment retained much more structure than the upstream side, even possessing some undamaged original surfaces on both the inside and outside diameters. Because of the significant burning upstream of the ball element and on the upstream face of the ball, the evidence indicated that the fire's local origin was upstream of the ball element, in the proximity of the upstream seat retainer, and that the fire progressed over the top and around both sides of the ball rather than following the normal flow path through the inside of the ball. To produce these patterns, it was considered probable that the upstream seat was compromised early in the fire, allowing flow to carry combustion products around and over the ball rather than through the ball element's interstage.

Figure 7 depicts a view from the backside of the valve looking upstream and shows the relatively clean (free of combustion debris) downstream surface of the ball.

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This figure depicts the ball element in a position approximating its position at the time of the fire (as do Figures 4-6) and shows the substantial burning of the upstream face of the ball and the relatively "clean" downstream face. Figure 7 also shows that the lower shaft was severely burned and eroded below the ball. All of these burn patterns were consistent with a local origin proximate to the upstream seat retainer and a preference for upstream to downstream burning propagating on top of and around both sides of the ball, severing the top shaft and undercutting the lower shaft, and burning out through the body on both sides of the valve.

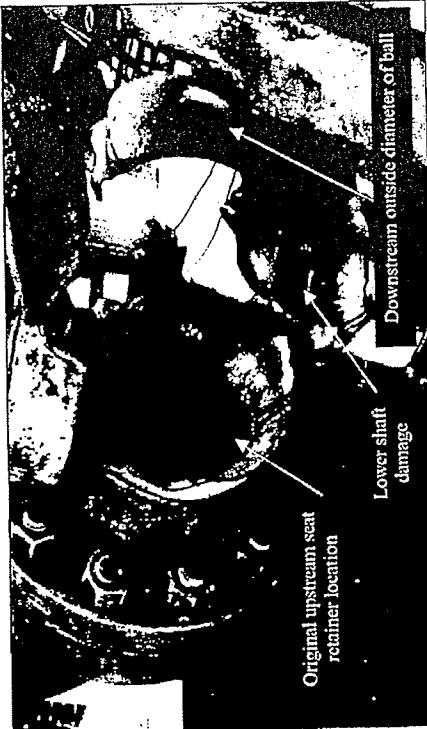


FIG. 7 – Burn patterns on backside of incident valve.

Ignition Mechanisms and Flow Analysis

The fire damage and melt/flow patterns discussed above favor ignition within the upstream seat retainer. Analysis of the lubricating grease, which packed the wavy spring cavity in the seat, was sampled from the exemplar valve and found to be consistent with a hydrocarbon-based grease, as specified. This same lubricant is believed to have also been within the incident valve at the time of the fire. The probable presence of hydrocarbon grease in the seat retainer suggested that contaminant promoted ignition could have occurred while the valve was opening due to the natural stroke of the contaminated wave springs and the re-establishment of flow through the valve. However, conditions understood to have existed prior to the fire gave credibility to another potential ignition source as well. Though the valve was being opened with a low differential pressure, initial calculations using standard isentropic flow equations for compressible fluids estimated the flow velocities through the valve to be sufficient to

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potentially ignite particles. Because of this, particle impact ignition was not ruled out as a contributing ignition source, though the actual gas velocities through the valve were difficult to calculate with accuracy due to the unpredictable influence of the ball's interstage.

To further understand the most probable ignition scenario and to relate the melt/flow patterns observed to the initial ignition mechanism, a model of the valve was developed to approximate the geometric relationships of the valve's internal. Based on our reconstruction of the burn patterns, the ball was believed to have been at approximately 20 degrees open when the incident occurred. Figure 8 depicts a two dimensional diagram of the ball and seat assembly as a top view cross-section with the valve open 20 degrees as indicated by the reconstruction. A Computational Fluid Dynamics (CFD) [2] software program was then applied to the model to more accurately calculate the gas flow conditions through the valve. Of specific interest were gas velocities and vector streamlines, as well as pressure and temperature conditions throughout the valve. The CFD program predicted gas velocity profiles through the valve at both 10 degrees and at 20 degrees open to simulate the flow conditions as the ball just comes off the seat with a pressure differential of 550 psig (3.8 MPa) upstream and 510 psig (3.5 MPa) downstream. Figure 9 shows the results of the CFD analysis as it pertained to the flow velocities and flow streamlines at 20 degrees open.

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consequence of reduced gas expansion resulting from the interstage pressure. The downstream velocity exhibited an extended region of high velocity flow along the flow-impinged edge of the valve outlet and mating flange. The CFD analysis also predicted very turbulent flow downstream of the valve. The CFD analysis indicated that the pressure within the interstage of the ball was approximately 530 psig (3.65 MPa). The velocity upstream and downstream pressures (approximately 300 ft/s (90 m/s) to approximately 150 to 200 ft/s (45 to 60 m/s) along the downstream surface of the ball's interstage and swirl inside the interstage region. This swirling flow would be expected to produce a very low velocity stagnation region in the center of the ball element's interstage. The upstream flow conditions were predicted to be low in velocity and turbulence, except for the area immediately around the flow opening.

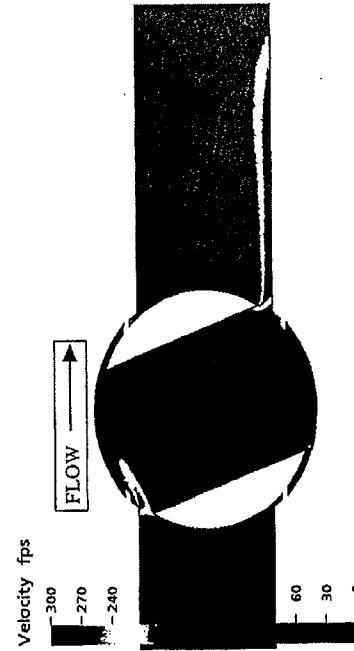


FIG. 9 – CFD model of velocity streamlines for incident valve upon opening.

Ignition Mechanisms Discussion

The WHA CFD analysis provided a significant aid to the reconstruction of the active ignition mechanisms and analysis of the propagation. Since the origin of the initial ignition was associated with the upstream seating assembly based on the burn patterns and reconstruction analyses, and since the valve was being opened at the time of the fire, two primary ignition mechanisms were indicated: particle impact and contaminant promoted ignition. The characteristic elements of each of these mechanisms were present at the time the valve was being opened but determining which mechanism provided the initial energy proved difficult.

The characteristic elements for particle impact ignition include the presence of particles, high gas velocities, impingement locations, and flammable materials [3]. Test

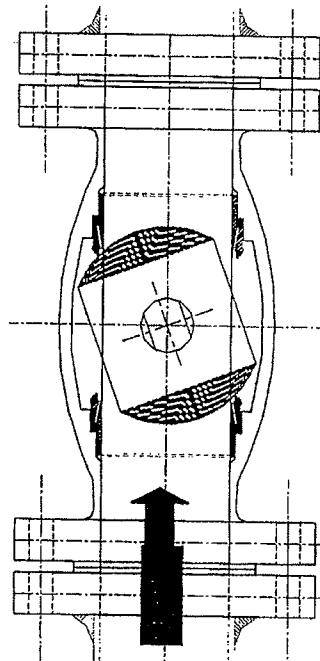


FIG. 8 – Two-dimensional top view model of the oxygen wetted region of the incident valve.

The WHA CFD analysis predicted that the gas velocity would have approached 300 ft/s (90 m/s) immediately downstream of the valve's seat both where the flow entered the ball's interstage (upstream) and where flow exited the interstage (downstream). This velocity was consistent with the approximate gas velocities calculated through compressible gas flow equations, as noted above. It was considered noteworthy that the upstream velocity profile was not as severe as the downstream profile. The upstream velocities decayed very rapidly as the flow entered the interstage, probably as a

data has shown that gas velocities greater than approximately 150 ft/s (45 m/s) are capable of supporting particle ignition in oxygen [4]. Further, design guides for oxygen systems recommend limiting gas velocities to below 100 ft/s (30 m/s) to minimize particle impact ignition [5]. The CFD analysis indicated that flow velocities in excess of these thresholds were developed as the flow was sweeping past the upstream seat retainer and leading edge of the ball element (Figure 9). The velocity streamlines indicate that flow was projected toward the middle of the valve body on the front side of the valve (Figure 9), creating potential particle impingement locations on the leading edge of the ball and along the inside wall of the front side of the valve. It is known that particles entrained in the gas flow develop their velocities more slowly than the gas due to inertial resistance and would likely not accelerate until they were being swept past the upstream seat. It is also known that particles entrained in the gas flow tend to resist changing direction rapidly due to sudden changes in the gas flow direction. As a consequence entrained particles would be directed onto the wall of the valve body, which was geometrically the most likely particle impact target. Either particle impact ignition at the seat retainer itself (less favored) or against the valve body (more favored) would be expected to cause intense burning of the front side of the valve and rapidly involve the downstream ball element and piping. For ignition by particle impact, based on the flow predicted by the CFD program, the fire would be expected to sweep around the backside of the ball element as well as involve the downstream inside diameter of the ball. It was noteworthy that these portions of the ball and valve did not exhibit this specific propagation pattern, and were relatively less damaged than the upstream components. Experience indicates that fire generally follows flow in these incidents, especially for metallic burning influenced by high velocity flow, which argued that the upstream seat retainer and ball element should have exhibited less damage if particle impact were the initial ignition mechanism.

The physical fire patterns however, indicated that the early combustion event did not sweep through the ball element's interface but instead swept over the top of the ball, around the backside of the valve, and under the ball, which was consistent with the fuel loading and kindling chain from contaminant promoted ignition initiating within the upstream seat retainer. The characteristic elements of contaminant promoted ignition include the presence of a flammable contaminant possessing the ability to promote ignition of surrounding materials and an active ignition mechanism to ignite the contaminant [6]. As noted above, gross quantities of hydrocarbon-based lubricating grease were believed to have been present throughout the seat assembly and outside diameter of the ball element. Contaminants of this nature require very low ignition energies as indicated by their low ignition temperatures and possess large heats of combustion [7]. The energy required to ignite the grease could have been provided simply from the dynamic motion of the spring-activated seal when being pressure loaded during opening. Flow of oxygen through and past the seat assembly would be expected to enhance this ignition through a mechanism similar to flow friction. Thus, the most probable cause and origin of this fire were related to ignition of contaminant in the upstream seat assembly which then propagated to the surrounding carbon steel valve parts.

Ball Valve Incident Conclusions

The most probable cause of this fire was contaminant promoted ignition, even though the characteristic elements for particle impact ignition were also present at the time the valve was opened. The CFD analysis provided key insight into each of these ignition mechanisms due to the visualization of the flow through the valve in its position at the time of the incident. The flow visualization allowed for identification of the most probable particle impact targets and the associated propagation based on the probable flow patterns through the valve once ignition developed. The CFD also confirmed the probable gas pressures and velocities inside the valve, which aided in evaluating the ignition and propagation scenario.

The investigation also demonstrated the importance of minimizing hydrocarbon-based contaminants in oxygen systems. Hydrocarbon contaminants require relatively little energy to ignite, yet burn vigorously in oxygen with energies capable of propagating a fire to other materials, especially if gross quantities are present, as was the case in this valve.

Finally, this analysis re-emphasized the extreme importance of opening valves

under a "no-flow" condition with an equalized pressure differential (delta-P). The industrial gas industry has long understood this issue and takes steps to avoid this circumstance; but, in some circumstances it is not well appreciated that even a 7% pressure differential (93% equalized), as was the case in this fire, will produce gas velocities that are at least 3 times greater than the preferred maximum velocities to avoid particle impact ignition and 10 times greater than those recommended by the Compressed Gas Association [8] for these materials for impingement flow³. A rule of thumb based upon isentropic flow equations for compressible fluids found reliable by WHA is that for any ratio of downstream to upstream pressure less than 97%, gas flow velocities greater than 200 ft/s (60 ms) will develop [9].

Butterfly Valve Fire

Valve and Incident Description:

Another fire was investigated during May of 2000 that involved a butterfly valve. Figure 10 depicts a wafer-style butterfly valve representative of the incident valve, although the actuator shown is different from the one actually installed. The valve was a 12 in. butterfly-style control valve specified as conforming to ANSI Class 600 and constructed with a Hastelloy C body, retaining ring, and control disc. The valve was also specified to have a PCTFE seat ring, Viton back-up ring, fiberglass/PTFE thrust bearing, and Inconel 718 shaft and pin. Figure 10 also depicts a representative check valve typical of the valve installed immediately downstream of the incident valve (several pipe diameters). This valve was specified as a 12 in. ANSI Class 900, wafer-style, "Duo-Chek" design with two plates sealing on a metal-to-metal interface. The valve body, plates, stop pin, hinge pin, spring, and bearings were all specified as Monel.

³ Velocities calculated using standard isentropic flow equations for compressible gas flow. The well-known "velocity curve" in CGS G-4 recommends that for carbon steel at approximately 500 psig, gas velocities be limited to one-half of approximately 60 ft/s, or 30 ft/s (REF CGA G-4).

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burned out as combustion products, molten metal, and fire were directed down the pipeline.

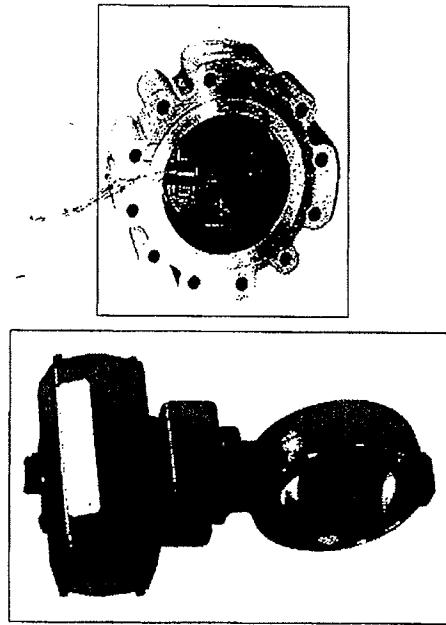


FIG. 10 – Valves typical of incident butterfly valve (left) and downstream check valve (right).

The butterfly valve was installed downstream of a newly constructed Air Separation Unit (ASU) that was in the final stages of start-up operations. The boost compressors associated with the ASU had been running for several hours, first on air, then on higher concentrations of oxygen, which were delivered to the valve inlet. During this process, the butterfly valve was closed and the gas mixture was being recycled through a recirculation loop until steady-state conditions could be achieved. After the system reached the required minimum oxygen concentration of 99.6%, recirculation of the oxygen was continued for approximately 1-1/2 to 2 hours before the butterfly valve was commanded to open. Based on previous operations, the system downstream was believed to have contained a low pad pressure of inert gas, but the exact constituents and conditions are unknown. The fire occurred while the valve control mechanism was being remotely opened and throttling flow developed. The internal fire swept into the downstream piping causing damage to a downstream check valve and several hundred feet of downstream piping. Figure 11 shows the fire-damaged condition of the butterfly valve and attached piping.

Figure 12 shows the fire-damaged condition of the downstream check valve housing as viewed through the pipe separation that occurred just downstream of this component. Based on inspections at the fire scene, the check elements were ejected from the valve and one check element was energetically expelled through the downstream pipeline elbow (shown in Figure 12), along with fire and combustion gases, into a support beam, which was knocked over by the impact. Several other downstream elbows also

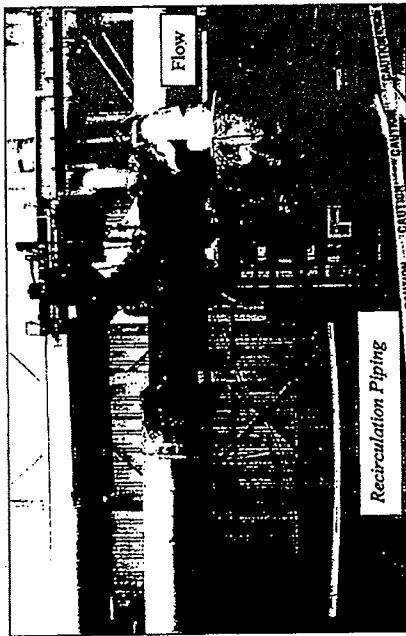


FIG. 11 – Remains of fire-damaged butterfly valve and attached piping.



FIG. 12 – Check valve and downstream piping.

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Burn Pattern Observations

A close up view of the fire-damaged condition of the butterfly valve is shown in Figure 13. Significant portions of the upstream and downstream flanges as well as much of the butterfly valve body were consumed during the fire. The area of primary consumption/mass loss for the valve and the attached flanges and piping was on the side shown in the foreground of these photos. The backside of the valve was still largely intact, with the exception of a small hole burned through the backside of the valve, although the interior metallic parts were fully involved in the fire. The upstream flange and portions of the pipe immediately upstream of the valve exhibited significant burning and were largely consumed. It was determined that both the upstream flange and piping immediately upstream of the butterfly valve were carbon steel, whereas the downstream flange was stainless steel and the downstream pipe spool was Monel. The valve body and trim pieces were all promoted during different stages of the fire and each exhibited

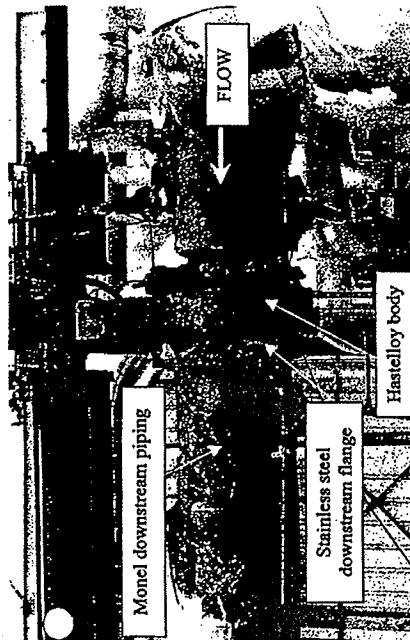


FIG. 13 - Close-up view of the fire-damaged butterfly isolation valve

partial consumption. The body wall thickness reduced considerably through burning, especially on the side shown in the foreground. The butterfly disc was still intact, but its lower shaft was severed through its cross section and the disc itself was consumed significantly on its downstream face and around its radius. The nonmetallic seat and backup seal and the metallic retainer were also significantly consumed. Intense melt/flow patterns were evident inside the valve body.

Figure 14 is a close up view of the burn patterns and mass consumption observed proximate to the valve. Most of the self-sustained burning was associated with the valve and the upstream carbon steel flange/pipe, though the downstream stainless steel flange

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was also burned where it mated to the valve. It was noteworthy that upstream of the burned out section of the upstream pipe, no evidence of combustion was observed, as can be seen in Figure 11. A clear demarcation of the fire-involved areas was observed and the piping upstream of this area, even within a few inches, was uninvolved. This observation is consistent with WHA experience that, components exhibiting the furthest upstream evidence of burning in a flow system are generally indicative of the origin of the fire.



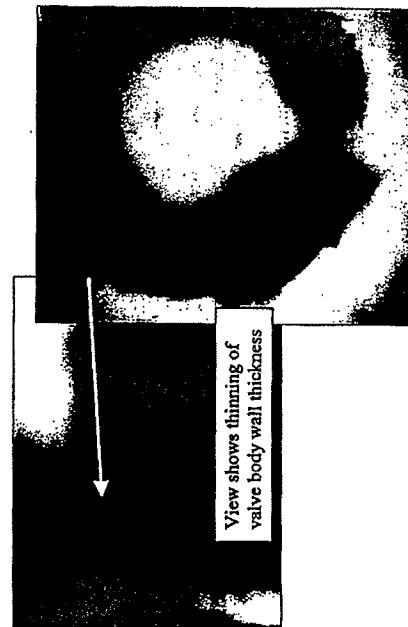
FIG. 14 -- Close-up photograph of valve consumption patterns.

The butterfly element is shown in Figure 15 looking through the burned-out section of the upstream pipe and flange. The butterfly element was fire eroded around its entire circumference but especially in the 3rd and 4th quadrants (180 to 360°, viewed from upstream, clockwise from the 12 o'clock position). The 3rd quadrant was especially involved and exhibited a local burned region that was significantly heavier than the rest of the butterfly disc. The Inconel 718 shaft at the 6 o'clock position was also heavily consumed and burning of the Hastelloy body in this proximity had extended down into the shaft-bearing region.

Figures 16 and 17 are X-ray views of the valve depicting the heavy burning of the valve components. WHA often uses radiography as a nondestructive tool in forensic investigations to show internal configurations of burned hardware and to aid in fire propagation analysis. It is important to note that these X-rays show areas of relative metal thickness/thickness and due to the intensity of the X-ray source wash out the thinnest sections of metal. Figure 16 depicts the significant thinning of the valve's Hastelloy body wall thickness as well as the material loss around the circumference of the



FIG. 15 – Close-up of upstream side of butterfly disc and retaining ring.



View shows thinning of
valve body wall thickness

FIG. 16 – X-ray view of body wall thinning and butterfly disc mass loss (note separation of lower shaft and consumption into lower bearing/bushing).

disc. Figure 16 clearly shows the areas of greatest fire involvement were in the 3rd quadrant of the valve, including complete separation of the Inconel 718 lower shaft. Figure 17 shows a close-up X-ray view of the lower shaft region of the butterfly disc depicting separation of the shaft below the disc.

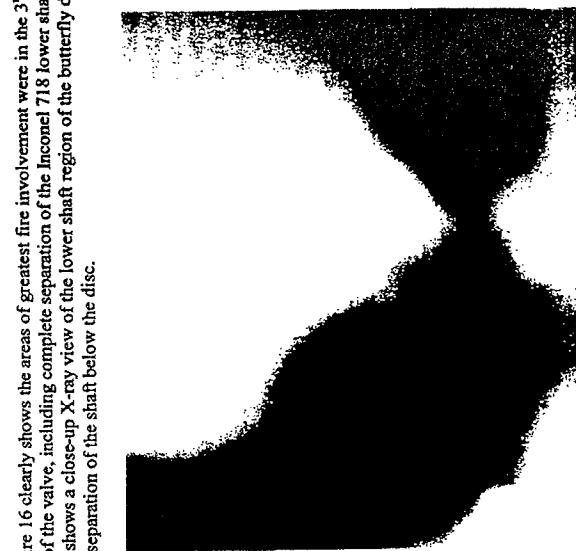


FIG. 17 – X-Ray view of burned butterfly disc and separation of lower shaft (viewed from upstream).

Materials Flammability and Ignition Mechanisms Discussion

It is noteworthy that based on previous promoted combustion testing the Hastelloy C materials used for the valve are generally considered situationally nonflammable (i.e., will not self-support combustion but will tend to self-extinguish) under these operating conditions [10]. Therefore, the degree of consumption exhibited by the valve was surprising. The significant consumption exhibited by the upstream carbon steel flange/pipe argued that the majority of the energy necessary to continue the Hastelloy combustion probably came from the self-sustained burning of the carbon steel flange/pipe. The melt/flow patterns also argued that the carbon steel flange/pipe were probably involved in the early stage kindling chain and therefore its ignition was considered critical to the reconstruction. Either direct ignition of the carbon steel by a mechanism such as particle impact or promoted ignition of the carbon steel by prior ignition of the nonmetallic seat and back-up seal assembly were considered probable for the circumstances understood to have existed prior to the fire.

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The Inconel 718 shaft was considered flammable under these conditions [1]. However, due to its thick configuration (approx. 2-in (5.1 cm) diameter), its kindling was probably also associated with being promoted by an energetic promoter such as the carbon steel flange/pipe and the seat/seal assembly. Furthermore it was relatively protected from the upstream flow by the Hastelloy disc and seat retainer ring, so would be less likely to ignite without being promoted by another kindling chain element.

Figure 18 illustrates the consumption patterns that were documented with reference to the butterfly disc and show the radial relationships of various burned components. The upstream pipe was burned out front approximately 120° to 30°, and consumed for a full 270° around the circumference. The valve seat retainer was burned

from the upstream flow by the Hastelloy disc and seat retainer ring, so would be less likely to ignite without being promoted by another kindling chain element.

Figure 18 illustrates the consumption patterns that were documented with

reference to the butterfly disc and show the radial relationships of various burned components. The upstream pipe was burned out front approximately 120° to 30°, and

consumed for a full 270° around the circumference. The valve seat retainer was burned

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NEWTON AND FORSYTH ON LARGE INDUSTRIAL OXYGEN VALVE FIRES

from approximately 150° to 330° and consumed for about 180° in the 2nd, 3rd, and 4th quadrants. The heavy consumption exhibited by the butterfly disc is also shown with the most significant material loss centered at approximately 210°. The body of the valve exhibited significant consumption patterns between approximately 240° and 300° around the circumference.

Figure 19 illustrates the valve burn patterns on both a side cross-section and a top cross-section of the butterfly valve in its probable position at the time of the fire. The shaded areas indicate where material was consumed by the fire. Heavy burning is shown proximate to the upstream flange/pipe, around the radius of the disc, and involving the lower shaft and inner wall of the valve body.

These illustrations were helpful to the reconstruction in estimating the areas of earliest involvement, as compared to the burned areas that were probably promoted by other valve/pipe components already burning, and in evaluating the active ignition mechanisms. Based on the melt/flow reconstruction and failure analysis, two ignition mechanisms were considered active: particle impact on the carbon steel flange or a kindling chain mechanism in the lower section of the valve.

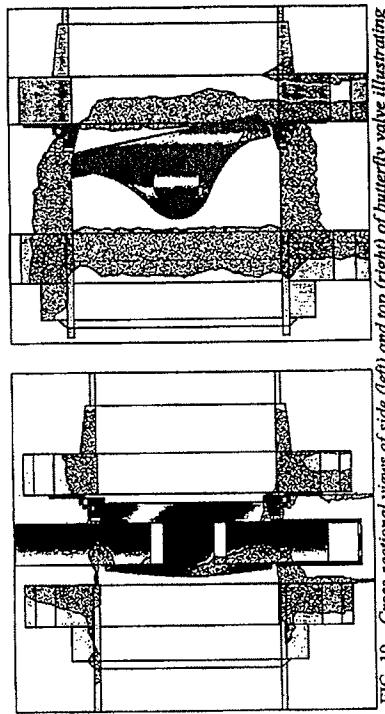


FIG. 19 – Cross-sectional views of side (left) and top (right) of butterfly valve illustrating burn patterns and estimates of material consumption.

First, based on the conditions within the valve at the time of the fire, the characteristic elements required for particle impact ignition were all present and active. High gas velocities occurred proximate to impingement sites on flammable materials, namely, the upstream carbon steel flange/pipe. The illustration of the top cross-section in Figure 19 illustrates that for a butterfly valve of this size, the control element will sweep past the upstream flange interface, which during opening under a pressure differential will develop throttling flow. Since the most significant propagation and promoted combustion was in the lower segment of the valve, between roughly 180° and 240° (see Figure 18), the kindling chain in this area was considered important. However, particle

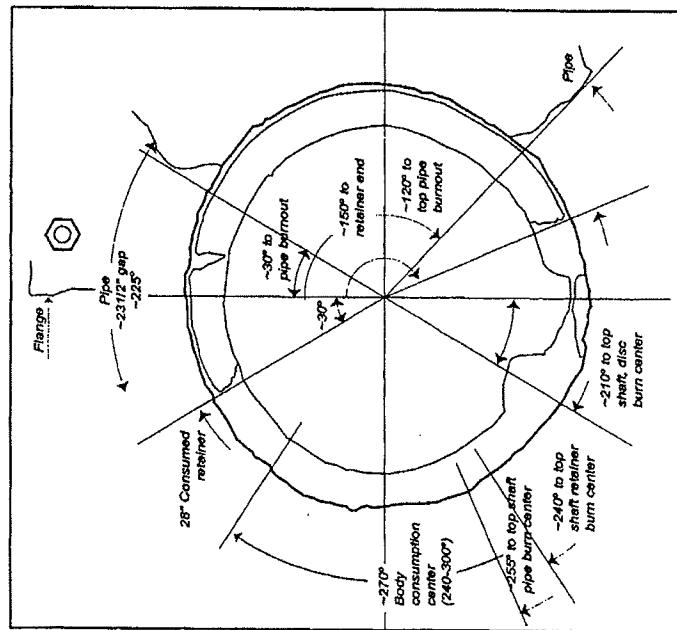


FIG. 18 – Illustration of consumption patterns pertaining to the butterfly disc, retainer rings, and upstream flange/pipe interface

impact in this proximity was not considered strong since during the first approximate 10° to 20° of opening (based on the rotation of the disc for the 90° full-open valve) the butterfly disc would still be in contact with the seat in the lower portion of the valve and flow velocities would be low (upon opening, the 3 o'clock and 9 o'clock positions around the disc would first be exposed to flow and associated high gas velocities). Thus, based on the burn and melt/flow patterns, particle impact ignition was not considered the primary cause of the fire, but instead promoted combustion of the carbon steel flange by a kindling chain mechanism was considered the most active ignition mechanism where the fire patterns exhibited their greatest intensity.

The heavy involvement in the lower section of the valve was considered especially important, and chemical analysis of the materials in that area was obtained. The analysis indicated that one component of the friction bushing was a phenolic-based material. Phenolics are common constituents of bushings and tend to exhibit an Autogenous Ignition Temperature (AIT) in the range of 411°F (155°C), which was close to the 270°F (132°C) process temperature. Additional frictional heating during valve opening was considered sufficient to generate phenolic ignition. Although it was considered unlikely that the limited amounts of phenolic-based binder in the bushing would have been capable of directly igniting the Inconel 718 shaft or the adjacent carbon steel flange/pipe, promoted ignition of the PCTFE seat and Viton backup ring by the phenolic was considered probable, especially in the lower segment of the valve immediately around the shaft where the flow was minimized. Combined PCTFE and Viton ignition would be expected to kindle the adjacent carbon steel flange and the Inconel 718 shaft. Due to the heavy burning low in the valve and the clear kindling chain associated with the phenolic/seal ignition, promoted ignition of the valve was favored over particle impact.

Butterfly Valve Incident Conclusions

The melt/flow patterns were consistent with the origin of the fire being at the upstream interface of the butterfly valve. The unusual combustion of the Hastelloy C body and disc element of the valve supported that the upstream carbon steel flange and pipe were involved in the early kindling chain and substantially increased the total energy release and degree of consumption. The extensive burning in the lower section of the valve favored an initial kindling chain from the phenolic binder to the seat/seal assembly leading to ignition of the carbon steel flange and pipe.

At least two lessons were indicated by this failure analysis. First, while the valve materials were generally superior in compatibility, the overall construction of the valve provided for a kindling chain that led to promoted combustion of the carbon steel flange and pipe immediately upstream of the valve. Once the carbon steel combustion developed, its propagation dominated the continued burning of the valve and downstream system. Had this kindling chain not developed, it is probable that the energetic nature of the burnout would have been significantly reduced.

Second, the carbon steel upstream flange was vulnerable to ignition by either a kindling chain mechanism or by direct ignition from particle impact while the valve was being opened. To our knowledge, the prevalent industry standards do not sufficiently discourage the use of carbon steel in the manner in which it was used in this system. The

overall design, however, would have been improved by the use of a situationally nonflammable material directly upstream of the valve where high velocity flow could develop.

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EXHIBIT 63



PRAXAIR, INC.
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PRAXAIR STANDARD	EN-6
ISSUE DATE	11/01/63
REVISION DATE	2/20/02
EFFECTIVE DATE	3/20/02
WRITTEN BY	R. C. Enger
REVISED BY	A. V. Samant
APPROVED BY	R. Zawierucha
RELEASED BY	J. P. Bernard

MAXIMUM ALLOWABLE VELOCITIES
OF GASEOUS OXYGEN IN PIPING AND PIPING COMPONENTS
(INCLUDING PRESSURE AND NONPRESSURE VESSELS)

1.0 SCOPE

Materials used in oxygen equipment and in the construction of oxygen producing plants can burn when ignited in atmospheres above definable combinations of oxygen concentrations and pressures. This tendency is mitigated by proper material selection, by cleaning to remove combustibles and particulates that might act as ignition promoters, and by limiting the gas velocity in piping and components to reduce the probability of ignition caused by particle impact and/or adiabatic compression.

This Standard defines the limitations for oxygen gas velocity in piping and piping components (including pressure and nonpressure vessels) constructed of aluminum, aluminum-bronze, carbon steel, cast iron, stainless steel and other alloys for applications with oxygen concentrations above 23.5% and pressures up to 7000 PSIG (48.4 MPa).

Conditions outside the limits of this Standard shall be reviewed with the Corporate S&ES Manager of Operational Safety and the Materials Engineering Laboratory.

2.0 APPLICABLE STANDARDS

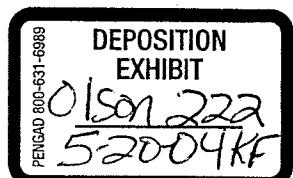
2.1 Praxair Standards

The following is a list of other Praxair Standards, Engineering Memorandum and code requirements specifically referenced in this document, selected references providing significant background pertinent to this Standard or documents which may reference or use this Standard. This list does not necessarily include all Standards that may be applicable to the subject matter. For other applicable Standards, refer to the Praxair Standards Index volume.

- EN-4 Design of Non-Cryogenic Oxygen Systems
- EN-18 Design of Cryogenic Systems

**RESTRICTED
FOR INTERNAL USE ONLY**

**NOTE: ITALIC PORTIONS OF THIS TEXT ARE
DESIGN SAFETY RELATED IN ACCORDANCE
WITH PRAXAIR STANDARD SA-5.**



Praxair Standard EN-6 (Rev. 2/20/02)

- EN-60 Flammability of Engineering Alloys in High-Temperature Oxygen Atmospheres
- GS-37 Specification for Cleanliness of Components Used for Ultrahigh Purity Supply Systems
- GS-38 Praxair Class 2 (Oxygen) Cleaning

2.2 External References

2.2.1 Compressed Gas Association

- CGA 4.4 Industrial Practices for Gaseous Oxygen Transmission and Distribution Piping Systems

2.2.2 American Society for Testing and Materials

- ASTM G-63 Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service
- ASTM G-88 Standard Guide for Designing Systems for Oxygen Service
- ASTM G-93 Standard Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments
- ASTM G-94 Standard Guide for Evaluating Metals for Oxygen Service
- ASTM STP 986 Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres, p.37

2.2.3 National Fire Protection Association

- NFPA 53 Guide on Fire Hazards in Oxygen Enriched Atmospheres

2.3 Referenced Laboratory Reports

- MEL TR 2438 Materials Engineering Laboratory Test Report
- MEL TR O-98-029 Materials Engineering Laboratory Test Report

Praxair Standard EN-6 (Rev. 2/20/02)3.0 GAS VELOCITY DESIGN CRITERIA FOR SYSTEMS CLEANED TO PRAXAIR STANDARD GS-383.1 Allowable Velocities for Flammable Materials

Except where specifically exempted in the other Figures and Tables herein, the curves shown in Figure 1 represent the maximum allowable velocities for oxygen gas in piping or components constructed of aluminum, aluminum-bronze, carbon steel, cast iron, stainless steel and other alloys for pressures up to 1000 PSIG (7.0 MPa) and temperatures up to 400°F (205°C).

Except where specifically exempted in the other Figures and Tables herein, the curves shown in Figure 2 represent the maximum allowable velocities for oxygen gas in piping or components constructed of aluminum, aluminum-bronze, carbon steel, cast iron, stainless steel and other alloys for pressures between 1000 PSIG (7.0 MPa) and 5000 PSIG (34.6 MPa) to a maximum temperature of 400°F (205°C). For pressures in excess of 5000 PSIG (34.6 MPa), velocity exemption curves do not exist, and it is necessary to use alloys which are combustion resistant at the higher pressures (see Table 1A). For very high-pressure systems, other safety precautions not within the scope of the Standard, related to factors such as mechanical properties and toughness may have to be considered. This is due to the increased stored energy in gaseous systems as pressure increases.

3.2 Materials Exempt from Velocity Limitations-Tables

Table 1A lists materials (wrought and cast alloys) with high copper or nickel content which are exempt from velocity limitations for systems cleaned to Praxair Standard GS-38, Praxair Class 2 (Oxygen) cleaning and operating at pressures up to 5000 PSIG (34.6 MPa), 6000 PSIG (41.5 MPa) and 7000 PSIG (48.4 MPa) irrespective of oxygen concentration. Data for the 6000 PSIG (41.5 MPa) and 7000 PSIG (48.4 MPa) cases was generated by National Aeronautics and Space Administration (NASA). The maximum temperature limitation is 400°F (205°C). There are no thickness limitations on these materials and they are velocity exempt up to the pressures cited. However, extremely thin thicknesses are more prone to ignition than thicker cross sections and should be avoided where possible in components.

Table 1B lists selected materials (wrought alloys) which are velocity exempt in oxygen systems to specific pressure limits ranging between 200 PSIG (1.48 MPa) and 1500 PSIG (10.4 MPa). Note that with the exception of Inconel 600 and Stellite 6, material thickness shall be 0.125 inch (3.18 mm) minimum, and maximum temperature limitation is 400°F (205°C). Inconel 600 has no minimum thickness limits up to the maximum pressure cited, 1000 PSIG (7.0 MPa). Stellite 6 has no minimum thickness limits up to 500 PSIG (3.55 MPa).

Table 1C lists selected materials (cast alloys) which have variable exemption pressure limits for different thickness [0.125 inch (3.18 mm), 0.250 inch (6.35 mm) and 0.375 inch (9.53 mm)]. It is acceptable to interpolate pressure limits based on intermediate thicknesses. Extrapolation outside of these thicknesses is not permitted.

Table 1D lists selected hard facing alloys, weld filler metals and their exemption pressures in oxygen systems. Note that the minimum thickness is 0.125 inch (3.18 mm) and the

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maximum temperature limitation is 400°F (205°C) except for Stellite 6. There is no minimum thickness requirement for Stellite 6 up to the maximum pressure cited, 500 PSIG (3.55 MPa). However, extremely thin thicknesses are more prone to ignition and more susceptible to spalling as compared to thicker cross sections, and should be avoided where possible in components.

For temperatures above 400°F (205°C) consult Praxair Standard EN-60 for elevated temperature applications involving oxygen-enriched atmospheres.

3.3 Special Exemptions in VPSA Applications and Lower Purity Applications

Flammability tests in selected simulated VPSA gas mixtures have resulted in the following exemptions:

1. *Aluminum casting alloys 319 (UNS No. A03190) and 356 (UNS No. A03560) are exempt from velocity limitations at pressures up to 75 PSIG (0.62 MPa) in oxygen environments having a nominal composition of 95% O₂ - 4% Ar - 1% N₂ if the material thickness is greater than 0.125 inch (3.18 mm). The N₂ content cannot exceed 2% at a maximum oxygen concentration of 95%.*
2. *Aluminum casting alloy G Al Si9 (UNI 3051) is exempt from velocity limitations at pressures up to 150 PSIG (1.14 MPa) in oxygen environments having a nominal composition of 93% O₂ - 4.5% Ar - 2.5% N₂ if the material thickness is greater than 0.125 inch (3.18 mm). The N₂ content cannot exceed 3.5%.*
3. *Aluminum alloys 5083 (UNS No. A95083) and 5183 (UNS No. A95183) are exempt from velocity limitations at pressures up to 150 PSIG (1.14 MPa) in oxygen environments having a nominal composition of 93% O₂ - 4.5% Ar - 2.5% N₂, if the material thickness is greater than 0.125 inch (3.18 mm). The N₂ content cannot exceed 3.5%.*
4. *Aluminum alloy 6061 (UNS No. A96061) is exempt from velocity limitations at pressures up to 50 PSIG (0.45 MPa) in oxygen environments having a nominal composition of 95% O₂ - 4% Ar - 1% N₂, if the material thickness is greater than 0.125 inch (3.18 mm). The N₂ content cannot exceed 2%.*
5. *Carbon steel is exempt from velocity limitations at pressures up to 8 PSIG (0.16 MPa) in VPSA oxygen environments having a maximum oxygen concentration of 95%, - bal. Ar and N₂, if the material thickness is 0.25 inch (6.35 mm) or greater.*

3.4 Material Exemptions from Velocity Limitations-Figures

Curves shown in Figures 3 through 14 define regimes where certain materials are exempted from the maximum velocity limitations in Figures 1 and 2. These figures allow the reduced flammability tendencies of materials in reduced purity oxygen enriched atmospheres to be exploited.

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Note: With the exception of Hastelloy C-276 (Figure 8), the exemption curves in Figures 3 through 6 and 8 through 12 are only applicable where material thicknesses are 0.125 inch (3.18 mm) or greater (see Paragraph 6.1). At pressures up to 500 PSIG (3.55 MPa), Hastelloy C-276 (Figure 8) is exempt from minimum thickness limitations and it is also velocity exempt; however, at pressures above 500 PSIG (3.55 MPa), the minimum thickness limit is 0.125 inch (3.18 mm) or greater and the velocity guidelines of Figures 1 and 2 are applicable. Figures 7, 13 and 14 address thicknesses greater than 0.125 inch (3.18 mm), 0.250 inch (6.35 mm) and 0.375 inch (9.53 mm).

To identify figures that cover specific materials, the following guidance is provided. Some of the alloy names cited in this Standard may be registered trademarks:

Alloy	UNS Number	Major Alloying Elements	Reference Figure
Aluminum			
1100	A91100	99 min. Al	4
3003	A93003	97.5Al, 1Mn, 0.6Si, 0.7Fe, 0.2Cu	4
5083	A95083	94.8Al, 4.5Mg, 0.7Mn	4
5183	A95183	94.5Al, 4.8Mg, 0.7Mn	4
6061	A96061	98.4Al, 1.0Mg, 0.6Si	4
Aluminum Bronze	Various	83-95Cu, 5-11Al, 0-4Fe	4
Carbon Steel	Various	99Fe	3
Cast Iron (Gray)	F10006	93.9Fe, 3.2C, 2.1Si, 0.8Mn	6
Cast Iron (Ductile)	F32800	93.3Fe, 3.6C, 2.7Si, 0.4Mn	6
CA 6NM (Cast Stainless)	J91540	83Fe, 12Cr, 4Ni, 1Mn	6
Cast Versions of 304, 304L			
CF8	J92600	67Fe, 19.5Cr, 10Ni, 2Si, 1.5Mn	7
CF3	J92500	67Fe, 19.5Cr, 10Ni, 2Si, 1.5Mn (Low Carbon)	7
Cast Versions of 316, 316L			
CF8M	J92900	64.5Fe, 19Cr, 10Ni, 3Mo, 2Si, 1.5Mn	14
CF3M	J92800	65Fe, 19Cr, 10Ni, 3Mo, 1.5Si, 1.5Mn (Low Carbon)	14
Hastelloy C-22	N06022	56Ni, 21Cr, 13.5Mo, 4Fe, 3W, 2.5Co	9
Hastelloy C-276	N10276	56Ni, 16Mo, 15.5Cr, 5Fe, 4W, 2.5Co, 1Mn	8
Hastelloy G-3	N06985	42Ni, 22Cr, 19Fe, 7Mo, 5Co, 2Cu, 1W, 1Mn, 1Si	5
Hastelloy G-30	N06030	37Ni, 29Cr, 18Fe, 5Mo, 5Co, 3W, 2Cu, 1Mn	9
Hastelloy X	N06002	46Ni, 22Cr, 18.5Fe, 9Mo, 1.5Co, 1W, 1Mn, 1Si	8
Haynes 25	R30605	49.5Co, 20Cr, 15W, 10Ni, 3Fe, 1.5Mn, 1Si	6
Incoloy 825	N08825	41Ni, 32Fe, 21Cr, 3Mo, 2Cu, 1Mn	4
Inconel 718 (Precip. Hard)	N07718	53Ni, 22Cr, 15Fe, 5Nb, 3Mo, 1Co, 1Ti	3
Inconel 625	N06625	60.5Ni, 22Cr, 9Mo, 5Fe, 3.5Nb	6
INCO A	W86133	70Ni, 15Cr, 9Fe, 2Mn, 2Cb, 1.5Mo, 0.5Si	12
Ni-Resist, Type 2, Type D2	F41002	72Fe, 20Ni, 3C, 2Si, 2Cr, 1Mn	6
Stn. Steel (Carp 20 Cb-3)	N08020	35Fe, 35Ni, 20Cr, 3.5Cu, 2.5Mo, 2Mn, 1Si, 1Cb	5

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Alloy	UNS Number	Major Alloying Elements	Reference Figure
Stainless Steel (Wrought)			
304	S30400	69Fe, 19Cr, 9Ni, 2Mn, 1Si	5
304L	S30403	69Fe, 19Cr, 9Ni, 2Mn, 1Si (Low Carbon)	5
316	S31600	65.5Fe, 17Cr, 12Ni, 2Mn, 2.5Mo, 1Si	13
316L	S31603	65.5Fe, 17Cr, 12Ni, 2Mn, 2.5Mo, 1Si (Low Carbon)	13
Stn. Steel, 17-4 PH(H1150)	S17400	75.5Fe, 15.5Cr, 4Ni, 4Cu, 1Si	8
Stainless Steel, 410	S41000	85.5Fe, 12.5Cr, 1Mn, 1Si	10
Stainless Steel, 430	S43000	81Fe, 17Cr, 1Mn, 1Si	11
Stainless Steel, 904L	N08904	43Fe, 26Ni, 22Cr, 4.5Mo, 2Mn, 1.5Cu, 1Si	10
Stainless Steel, AL6XN	N08367	44.5Fe, 24.5Ni, 21Cr, 6.5Mo, 2Mn, 1Si, 0.25N	12
Titanium (Nb-55 Ti)		55Ti, 45Nb	10
Titanium CP (Pure)	R50250	99.5Ti	11

Unified Number System (UNS) numbers are provided to ensure precise identification for alloys which might be misidentified through the use of brand names such as Inconel, Hastelloy, etc.

The curves shown in Figures 1 through 14 are valid under the following conditions:

3.4.1 *The oxygen content of the gas is 23.5% or greater.*

3.4.2 *The pipe and components shall be cleaned for oxygen service in accordance with Praxair Standard GS-38. Nonmetallic materials used shall be oxygen compatible.*

3.4.3 *The temperature parameter for each curve in Figures 1 through 14 is the temperature of the oxygen gas or pipe (or component) wall, whichever is greater.*

3.4.4 *The system shall be operated so that large temperature increases due to adiabatic compression cannot occur (e.g., from the rapid opening or closing of a valve or regulator). Specific methods to ensure this are beyond the scope of this Standard.*

3.4.5 *Where an oxygen stream impinges directly against a surface (such as gas entering via a side connection), the maximum allowable velocity at the point of impingement is one half of the Figures 1 and 2 curve values unless the surface under impingement is an exempt material from Tables 1A, 1B, 1C or Figures 3 through 14 that is suitable for the design conditions. All alloys not found in Tables 1A, 1B or 1C that are used in impingement applications shall be approved by the Corporate S&ES Manager of Operational Safety and the Materials Engineering Laboratory. Long radius or larger pipe bends and elbows (radius of curvature equal to or more than 1.5 times pipe size) are not considered an impingement condition and full curve values from Figures 1 and 2 may be applied.*

3.4.6 *Velocity-exempt materials shall be used for piping adjacent to valves and similar devices in high velocity service. See Praxair Standard EN-4 for criteria to determine the*

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specific types of valves and devices, and also when velocity-exempt material is required upstream as well as downstream.

3.4.7 *Screen material for strainers used in gaseous oxygen services in systems cleaned to Praxair Standard GS-38 shall be fabricated from Monel, Inconel 600, Hastelloy C-276, Nickel 200 or high purity (>98%) copper because of the effect of geometry on combustibility related to the 0.125 inch (3.18 mm) minimum thickness requirement. Support structure [0.125 inch minimum (3.18 mm)] can be SS 304 to 175 PSIG (1.31 MPa) and 316 to 300 PSIG (2.17 MPa) (Class 150). Materials that have compatible combustion resistance in oxygen service, as defined by this Standard or by test, may also be used.*

3.4.8 *Safety relief device setpoints shall not exceed the applicable exemption pressures listed for specific materials in Figures 3 through 14.*

3.4.9 *Relief and overflow valves from Praxair liquid storage tanks (including oxygen) may be aluminum. Based on Materials Engineering Laboratory Test Report 2438, dated 9/3/97, aluminum valves are approved to 5.5 PSIG (0.14 MPa) for this application.*

4.0 GAS VELOCITY DESIGN CRITERIA FOR HIGH-PURITY OXYGEN SYSTEMS CLEANED TO PRAXAIR STANDARD GS-37

Praxair Standard GS-37, Specification for Cleanliness of Components Used for Ultrahigh Purity Supply (UHP) Systems, cleaning is intended for high-purity product applications where particulate control and alloy inertness are required in concert with metal finishing techniques such as electropolishing. Products are also filtered to remove particulates. Since particulates of any significance from an ignition standpoint are eliminated from the system, higher exemption pressures are allowed and minimum thicknesses are waived up to a maximum pressure of 350 PSIG (2.51 MPa) for 316 and 316L stainless steel components which are the industry standard for UHP Service.

Table 2 lists maximum pressures for which the materials, normally used for high purity applications, are exempt from velocity limitations.

Except where specifically exempted in the other Figures and Tables herein, the curves shown in Figure 1 represent the maximum allowable velocities for oxygen gas in piping or components constructed of various materials suitable for UHP oxygen service for pressures up to 1000 PSIG (7.0 MPa) and temperatures up to 400°F (205°C).

Except where specifically exempted in the other Figures and Tables herein, the curves shown in Figure 2 represent the maximum allowable velocities for oxygen gas in piping or components constructed of materials suitable for UHP oxygen service for pressures between 1000 PSIG (7.0 MPa) and 5000 PSIG (34.6 MPa) to a maximum temperature of 400°F (205°C).

Note: Exemptions for materials are only applicable where thicknesses are 0.125 inch (3.18 mm) or greater (see Paragraphs 6.1 and 6.4), except where noted.

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Piping or components constructed of certain engineering alloys that can produce particulates through corrosion-related processes are not considered to be suitable for UHP oxygen service.

Figures 1 and 2 and Table 2 are valid under the following conditions:

4.1 *The oxygen content of the gas is 23.5% or greater, but usually is more than 99.99%. (Exemption limits in Table 2 may be increased for some materials used in high-purity systems cleaned to Praxair Standard GS-37 when the oxygen concentration is reduced. Consult the Materials Engineering Laboratory for these limits or use the values shown in Figures 3 through 14 as a conservative guide.)*

4.2 *The pipe or components shall be cleaned for high-purity oxygen service in accordance with Praxair Standard GS-37. Nonmetallic materials, if used, shall be oxygen compatible.*

4.3 *The temperature parameter for each curve in Figures 1 and 2 is the temperature of the oxygen gas or pipe (or component) wall, whichever is greater.*

4.4 *The system shall be operated so that large temperature increases due to adiabatic compression cannot occur (e.g., from the rapid opening or closing of a valve or regulator). Specific methods to ensure this are beyond the scope of this Standard.*

4.5 *Where the oxygen stream impinges directly against a metal surface (such as gas entering via a side connection), the maximum allowable velocity is one half the curve values found in Figures 1 and 2 unless the surface under impingement is an alloy from Table 2 that is exempt from the velocity limitations. Otherwise, the Corporate S&ES Manager of Operational Safety and the Materials Engineering Laboratory shall be consulted.*

4.6 *Velocity-exempt materials shall be used for piping adjacent to valves and similar devices in high-velocity service. See Praxair Standard EN-4 for criteria to determine the specific types of valves and devices, and also when velocity-exempt material is required upstream as well as downstream.*

4.7 *Screen materials for strainers used in gaseous oxygen services in systems cleaned to Praxair Standard GS-37 shall be fabricated from Monel, Nickel 200 or 99.9% copper.*

4.8 *Pressure relief device set points shall not exceed the applicable exemption pressures listed for specific materials in Table 2.*

4.9 *Systems designed for high-purity service and cleaned to Praxair Standard GS-37 shall be reviewed if the systems are contaminated with, or converted to, lower purity (i.e., "standard purity") product since different exemption criteria for materials will apply. Where necessary, Corporate S&ES Manager of Operational Safety and the Materials Engineering Laboratory shall be consulted.*

Praxair Standard EN-6 (Rev. 2/20/02)5.0 COMPONENTS CONTAINING BELLows

At this time, this Standard does not completely address the minimum thicknesses to which the velocity guidelines shown in Figure 1 are pertinent. With the consideration of the use of components with bellows thicknesses as low as 0.012 inch (0.3 mm) in oxygen-enriched atmospheres, it is required to verify that this material is not flammable at service conditions in Praxair Standard GS-38 cleaned systems rather than rely on velocity limitations to preclude ignition. The use of a liner to protect the bellows from the gas stream is another option. Monel is the preferred material for expansion joints used in high-purity oxygen. Bellows material fabricated from 321 stainless steel with a minimum thickness of 0.012 inch (0.3 mm) is exempt from velocity limitations at pressures up to 40 PSIG (0.38 MPa) at oxygen purities up to 50%. In Praxair Standard GS-37, cleaned systems, which are particulate free, the use of thin 316 or 316L bellow cross sections, previously cited, is permitted. However, the Praxair Standard GS-37 cleanliness level must be maintained in the system.

6.0 GENERAL

6.1 *The velocity exemptions for materials 0.125 inch (3.18 mm) thick or greater do not apply to components that have thin edges. Such thin-edged components shall be fabricated from materials listed in Table 1A, Inconel 600 for pressures up to 1000 PSIG (7.0 MPa) or Hastelloy C-276 for pressures up to 500 PSIG (3.55 MPa) or other materials shown to be suitable via flammability tests of thin specimens in oxygen-enriched environments at appropriate pressures and purities.*

6.2 *Other considerations for the design of gaseous and liquid oxygen systems may be found in Praxair Standards EN-4 and EN-18, respectively.*

6.3 *The oxygen velocity criteria shown in Figure 1 are not applicable for vent piping. The cleanliness of pressure relief valve and vent valve discharge piping is not maintained once a facility is on stream. The material for this and other piping where control over cleanliness cannot be maintained shall be combustion resistant at the service pressure that the pipe will encounter. Therefore, the vent discharge material shall be one that is exempt from the velocity limitations of Figure 1 at the service pressure.*

6.4 *The use of platings or surface treatment shall not be considered as a viable technique for improving or increasing velocity exemption pressures unless the improvements can be demonstrated via flammability tests. Some platings or surface treatments may actually cause an increase in the susceptibility of substrates to ignition and combustion. Electroless nickel and borides are examples of this effect.*

Weld overlays of Monel or certain hard facing alloys may be approved on a case-by-case basis. The major advantage of weld overlays is the improved bonding with the substrate, increased resistance to spalling/flaking and significantly increased thickness as compared to platings and other surface treatments.

Praxair Standard EN-6 (Rev. 2/20/02)

- 6.5 *The maximum possible system variables such as pressure and velocity, and not the nominal operating variables, shall be used for all materials selection and velocity guidelines in this Standard.*
- 6.6 For low-purity oxygen environments with a maximum purity of 40% and a maximum pressure of 100 psig (0.79 MPa), thickness limitations are waived for all ferrous alloys (wrought and cast carbon and stainless steels and other iron based alloys), cobalt/nickel alloys (Haynes, Hastelloys, Inconels, Incoloy, Stellites) and weld filler/hard facing materials listed in Table 1D.

Praxair Standard EN-6 (Rev. 2/20/02)TABLE 1A

Materials and Maximum Pressure Limits
Exempt from Velocity Limitations for Oxygen Systems Cleaned to Praxair Standard GS-38,
400°F (205°C) Maximum Allowable Temperature

Alloy	UNS Number	Max. System Pressure for which Velocity Limitations are Exempted PSIG/MPa	Major Alloying Elements (%) ⁽²⁾
Electrolytic Tough Pitch Copper	C10200	7000 (48.4)	99.9 Cu
Phosphorus-Deoxidized Copper	C12200	7000 (48.4)	99.9 Cu
Beryllium Copper	C17200	5000 (34.6)	98.1 Cu, 1.9 Be
Tin Bronze	C90300	6000 (41.5)	87 Cu, 8 Sn, 4 Zn, 1 Ni
Tin Bronze	C90700	6000 (41.5)	89 Cu, 11 Sn
Navy M Tin Bronze	C92200	6000 (41.5)	87 Cu, 6 Sn, 5 Zn, 1 Pb, 1 Ni
90-10 Cupronickel	C70600	5000 (34.6)	87 Cu, 10 Ni, 1 Fe, 1 Mn, 1 Zn
70-30 Cupronickel	C71500	5000 (34.6)	67 Cu, 31 Ni, 1 Mn, 0.7 Fe
Red Brass	C23000	7000 (48.4)	85 Cu, 15 Zn
Free Cutting Brass	C36000	6000 (41.5)	62 Cu, 34 Zn, 3 Pb, 0.3 Fe
Admiralty Brass	C44300	6000 (41.5)	72 Cu, 27 Zn, 1 Sn
Naval Brass	C46400	6000 (41.5)	60 Cu, 39 Zn, 1 Sn
Nickel 200	N02200	7000 (48.4)	99 Ni, 0.4 Fe, 0.25 Cu
Berylco 440		5000 (34.6)	97.5 Ni, 2 Be, 0.5 Ti
INCO 141 Weld Filler	W82141	5000 (34.6)	97 Ni, 2.5 Ti, 0.3 Al
Nichrome V	N06003	5000 (34.6)	77 Ni, 20 Cr, 2 Mn, 1 Fe
Monel 400	N04400	7000 (48.4)	67 Ni, 32 Cu, 1 Fe
Monel K-500	N05500	7000 (48.4)	66.5 Ni, 30 Cu, 2.8 Al, 0.7 Ti
M-35-1 ⁽³⁾	N24135	5000 (34.6)	64 Ni, 29.5 Cu, 3.5 Fe, 1.2 Si, 1 Mn, 0.5 Nb, 0.3 C
M-35-2 ⁽³⁾	N04020	5000 (34.6)	62.3 Ni, 29.5 Cu, 3.5 Fe, 2 Si, 1.5 Mn, 0.5 Nb, 0.3 C

Notes:

- 1) No thickness restrictions; however, extremely thin thicknesses may affect flammability characteristics and may be a significant design consideration.
- 2) Nominal composition in weight % - May not add up to 100% in all cases.
- 3) Cast analogs of Monel; see ASTM A494.

Praxair Standard EN-6 (Rev. 2/20/02)

TABLE 1B

Wrought Alloys and Maximum Pressure Limits Exempt from Velocity Limitations
for Oxygen Systems Cleaned to Praxair Standard GS-38, 400°F (205°C) Maximum Allowable
Temperature - Thickness 0.125 Inch (3.18 mm) Minimum and 99.7+ O₂ Purity or Less

Alloy	UNS Number	Max. System Pressure for which Velocity Limitations are Exempted PSIG/MPa	Major Alloying Elements (%) ⁽¹⁾
Hastelloy C-4	N06455	1500/10.4	62.5 Ni, 16 Cr, 15.5 Mo, 3 Fe, 2 Co, 1 Mn
Colmonoy 6	W89606	1500/10.4	71.5 Ni, 15 Cr, 4.5 Fe, 4.5 Si, 3.5 B, 1 Co
Ultimet	R31233	1500/10.4	56 Co, 25 Cr, 9 Ni, 5 Mo, 3 Fe, 2 W
Haynes 230	N06230	1500/10.4	53 Ni, 22 Cr, 14 W, 5 Co, 3 Fe, 2 Mo, 1 Mn
Haynes 230	N06230	1000/7.0	As above but surface alonized, 10 mils max.
Inconel 117	W86117	1400/9.75	53 Ni, 23 Cr, 12 Co, 9 Fe, Bal Mn, Nb, Si
Stellite 6-B	R30016	1000/7.0	53 Co, 30 Cr, 4.5 W, 3 Ni, 3 Fe, 2 Si, 2 Mn, 1 C, 1.5 Mo
MP 35N	R30035	1000/7.0	35 Co, 35 Ni, 20 Cr, 15 Mo
Inconel 600 ⁽²⁾	N06600	1000/7.0	76 Ni, 15 Cr, 9 Fe
Inconel X750	N07750	1000/7.0	73 Ni, 15.5 Cr, 7 Fe, 2.5 Ti, 1 (Cb+Ta), 0.7 Al
Inconel 617	N06617	900/6.31	52 Ni, 22 Cr, 12.5 Co, 9.5Mo, 1.5 Fe, 1.2 Al
Haynes 214	N07214	900/6.31	77 Ni, 16 Cr, 4 Al, 3 Fe
Inconel 601	N06601	750/5.27	61 Ni, 23 Cr, 1.5 Al, 1 Mn, 1 Cu, Bal. Fe
Haynes 556	R30556	650/4.59	33 Fe, 22 Cr, 20 Ni, 18 Co, 3 Mo, 3 W, 1 Mn, Bal. Ta, Si, Al, N, La, Zr
Stellite 6 ⁽³⁾	R30006	500/3.55	55 Co, 29 Cr, 4.5 W, 3 Ni, 3 Fe, 1.5 Si, 1.5 Mo, 1.1 C, 1 Mn
353 MA	S35315	400/2.86	35 Ni, 25 Cr, 1.5 Mn, 1.5 Si; Bal Fe, (+Ce)
253 MA	S30815	400/2.86	21 Cr, 11 Ni, 1.8 Si, 0.6 Mn, Bal Fe, (+Ce)
Ni Aluminide IC 221M	—	400/2.86	80 Ni, 8 Al, 8 Cr, 2 Zr, 1 Mo
HR 160	N12160	300/2.17	36 Ni, 30 Co, 28 Cr, 3 Si, 3 Fe
Incoloy ⁽⁴⁾ 800	N08800	300/2.17	33 Ni, 21 Cr, 1.5 Mn, 1 Si, 0.75Cr, 0.4 Ti, Bal Fe
800H	N08810	300/2.17	33 Ni, 21 Cr, 1.5 Mn, 1 Si, 0.75Cr, 0.4 Ti, Bal Fe
800HT	N08811	300/2.17	33 Ni, 21 Cr, 1.5 Mn, 1 Si, 0.75Cr, 0.4 Ti, Bal Fe
Nitronic 50	S20910	300/2.17	20.9 Cr, 12.4 Ni, 5.5 Mn, 2.24 Mo, 0.77 Si, 0.29 Nb, 0.27 Cu, 0.21 V, 0.31 N, 0.07 Co, 0.02 C, Bal. Fe

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Alloy	UNS Number	Max. System Pressure for which Velocity Limitations are Exempted PSIG/MPa	Major Alloying Elements (%) ⁽¹⁾
X3 Ni Cr Mo 13-4 (A182- F6NM)	S41500	250/1.83	13 Cr, 4.5 Ni, 1 Mo, 1 Si, Bal. Fe
Nicrofer S6025 (602CA)	N06025	200/1.48	63 Ni, 25 Cr, 9.5 Fe, 2 Al, 0.3 (Ti, Y, Zr), 0.2 C
153 MA	S30415	200/1.48	19 Cr, 9 Ni, 1.2 Si, Bal Fe
321 SS	S32100	200/1.48	18 Cr, 11 Ni, Bal Fe (+Ti)
347 SS	S34700	200/1.48	18 Cr, 11 Ni, Bal Fe, (+Cb,Ta)
Inconel 725	N07725	100/0.79	57 Ni, 21 Cr, 9 Fe, 8 Mo, 3.5 Nb, 1.5 Ti

Notes:

- 1) Nominal composition in Weight % - May not add up to 100% in all cases.
- 2) Minimum 0.125 inch (3.18 mm) thickness is waived for Inconel 600.
- 3) Minimum 0.125 inch (3.18 mm) thickness is waived for Stellite (Stoody) 6.
- 4) Also applies to surface alonized, 10 mils maximum.

Praxair Standard EN-6 (Rev. 2/20/02)TABLE 1CCast Alloys and Maximum Pressure Limits

Exempt from Velocity Limitation for Oxygen Systems Cleaned to Praxair Standard GS-38,
400°F (205°C) Maximum Allowable Temperature - Variable Thickness and 99.7+% O₂

Alloy ⁽¹⁾	UNS Number	Max. System Pressure for which Velocity Limitations are Exempted PSIG/MPa	Minimum Thickness	Nominal Composition, Major Alloying Elements (%) ⁽²⁾
CG8M	J93000	350/2.51	0.125" (3.18 mm)	19.5 Cr, 11.0 Ni, 3.5 Mo, Bal. Fe
		500/3.55	0.250" (6.35 mm)	
		850/5.96	0.375" (9.53 mm)	
CN7M	N08007	450/3.20	0.125" (3.18 mm)	20.3 Cr, 32.5 Ni, 2.0 Mo, Bal. Fe
		650/4.58	0.250" (6.35 mm)	
		1100/7.69	0.375" (9.53 mm)	
CA6NM	J91540	400/2.86	0.125" (3.18 mm)	12 Cr, 4 Ni, 1 Mn, Bal. Fe
CW2M	N26455	2000/13.9	0.125" (3.18 mm)	65 Ni, 16 Cr, 16 Mo, 2 Fe, 1 Mn
M-35-1	N24135	5000/34.6	Note 3	64 Ni, 29.5 Cu, 3.5 Fe, 1.2 Si, 1 Mn, 0.5 Nb, 0.3 C
M-35-2	N04020	5000/34.6	Note 3	62.3 Ni, 29.5 Cu, 3.5 Fe, 2 Si, 1.5 Mn, 0.5 Nb, 0.3 C
Notes:				
1) These alloys are cast analogs of wrought materials as follows – CG8M/317 SS, CN7M/Carpenter 20Cb-3, CA6NM/Martensitic SS, CW2M/Hastelloy C-4, M-35-1 & M-35-2/Monel.				
2) Nominal composition in weight % - May not add up to 100% in all cases.				
3) No thickness restrictions; however, extremely thin thicknesses may affect flammability characteristics and may be a significant design consideration.				

Praxair Standard EN-6 (Rev. 2/20/02)TABLE 1D

Hard Facing Alloys, Weld Fillers and Maximum Pressure Limits
Exempt from Velocity Limitation for Oxygen Systems Cleaned to Praxair Standard GS-38,
400°F (205°F) Maximum Allowable Temperature - Thickness 0.125 Inch (3.18 mm) Minimum

Alloy	UNS Number	Max. System Pressure for which Velocity Limitations are Exempted PSIG/MPa
Inco 141	W82141	5000/34.6
Inco A	W86133	1500/10.4
Inco 82	N06082	1000/7.0
Inconel 117	W86117	1400/9.75
Inconel 617	N06617	900/6.31
Incoloy 65	N08065	900/6.31
Colmonoy 6	W89606	1500/10.4
Ultimet	R31233	1500/10.4
Hastelloy W	W80004	900/6.31
Stellite 6B	R30016	1000/7.0
Stellite (Stoody) 6*	R30006	500/3.55

*Minimum 0.125 inch (3.18 mm) thickness is waived for Stellite (Stoody) 6.

Praxair Standard EN-6 (Rev. 2/20/02)TABLE 2

Materials Which are Exempt from Velocity Limitations
for High-Purity Oxygen Systems Cleaned to Praxair Standard GS-37,
400°F (205°C) Maximum Allowable Temperature - Thickness 0.125 Inch (3.18 mm) Minimum
Except Where Noted (see notes below)

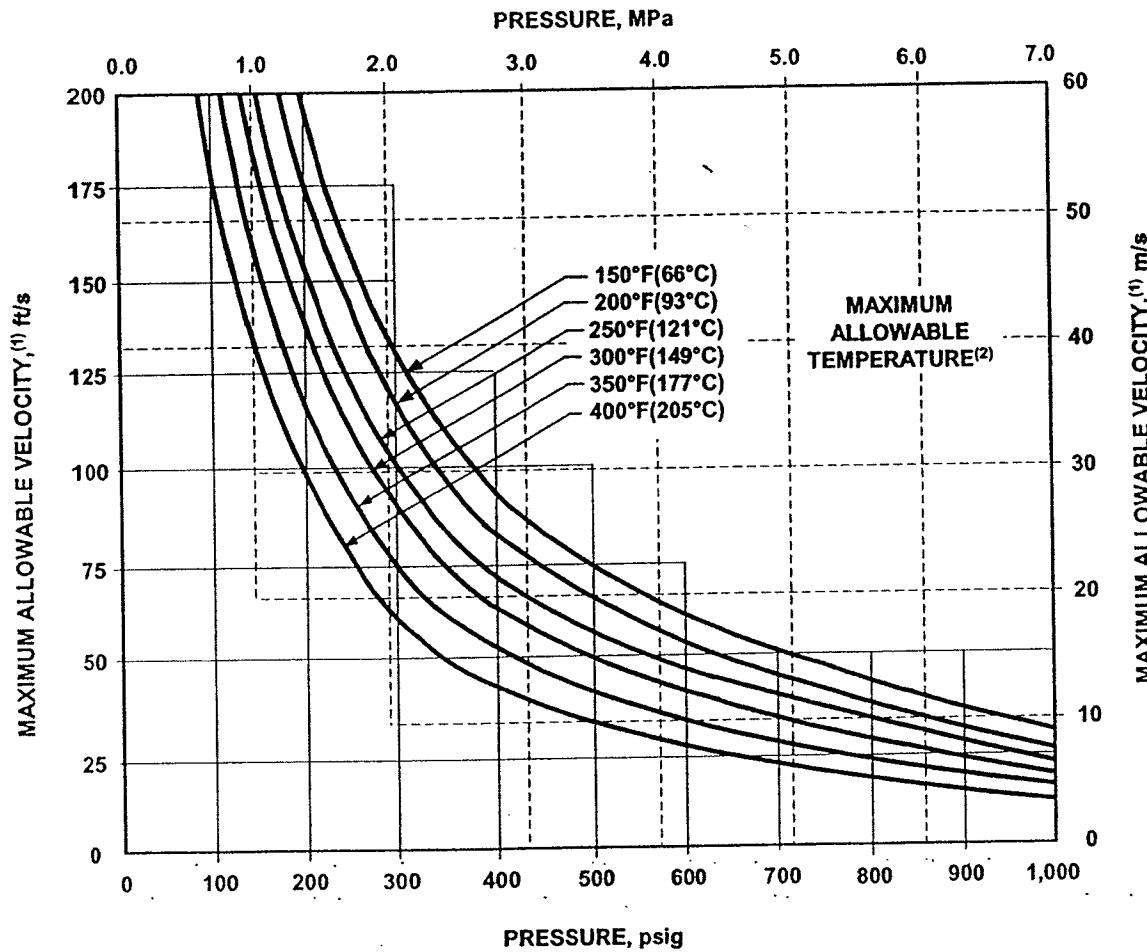
Alloy	UNS Number	Maximum System Pressure for which Velocity Limitations are Exempted ⁽¹⁾ PSIG/MPa
CW2M	N26455	3000/20.8
Hastelloy C-4	N06455	2000/13.9
Hastelloy C-22	N06022	1750/12.2
Hastelloy C-276 ⁽¹⁾	N10276	1500/10.4
Hastelloy G-3	N06985	1250/8.72
Hastelloy X	N06002	1000/7.0
Hastelloy G-30	N06030	500/3.55
Inconel 625	N06625	1500/10.4
Inconel 600 ⁽²⁾	N06600	1000/7.0
Incoloy 825	N08825	1000/7.0
Ultimet	R31233	1750/12.2
MP 35N	R30035	1000/7.0
904L Stainless Steel	N08904	500/3.55
Carpenter 20 Cb-3	N08020	500/3.55
AL6XN Stainless Steel	N08367	400/2.86
316 Stainless Steel ⁽³⁾	S31600	350/2.51
316L Stainless Steel ⁽³⁾	S31603	350/2.51
304 Stainless Steel	S30400	250/1.83
304L Stainless Steel	S30403	250/1.83

Notes:

- 1) Minimum thickness requirement for Hastelloy C-276 is waived up to a maximum pressure of 500 PSIG (3.55 MPa). Above that pressure, minimum thickness requirement pertains.
- 2) Minimum thickness requirement for Inconel 600 is waived up to a maximum pressure of 1000 PSIG (7.0 MPa). Above that pressure, minimum thickness requirement pertains.
- 3) Minimum thickness requirement for "electropolished" 316/316L stainless steel systems waived up to a maximum pressure of 350 PSIG (2.51 MPa). Cleanliness of components to Praxair Standard GS-37 must be verified and maintained once system is in operation.

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 1

Maximum Allowable Velocities of Gaseous Oxygen
in Aluminum, Aluminum-Bronze, Carbon Steel, Cast Iron, Stainless Steel
and Other Alloy Components (including pressure and nonpressure vessels)

**NOTES:**

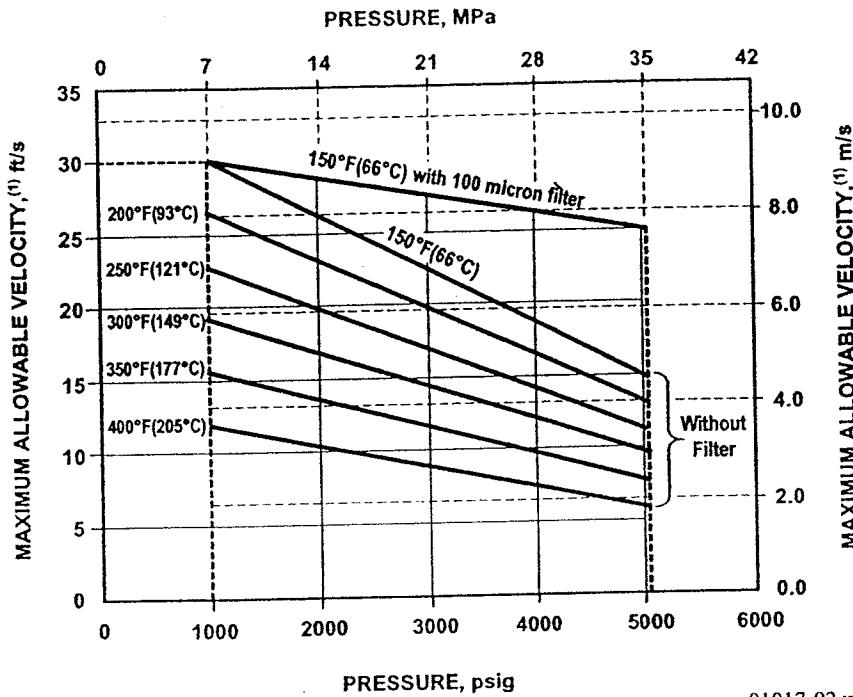
- (1) The maximum allowable velocity at impingement points is one-half the curve values.
- (2) The maximum allowable temperature of some materials (e.g. aluminum alloys) may be limited by other considerations. Consult the applicable codes and/or Materials Engineering.
- (3) The maximum allowable velocity is 200 ft/s (61 m/s).

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Praxair Standard EN-6 (Rev. 2/20/02)

FIGURE 2

Maximum Allowable Velocities of Gaseous Oxygen
in Aluminum, Aluminum-Bronze, Carbon Steel, Cast Iron, Stainless Steel,
and Other Alloy Piping and Piping Components (including pressure and nonpressure vessel)
at Pressures Between 1000 PSIG (7.0 MPa) and 5000 PSIG (34.6 MPa)

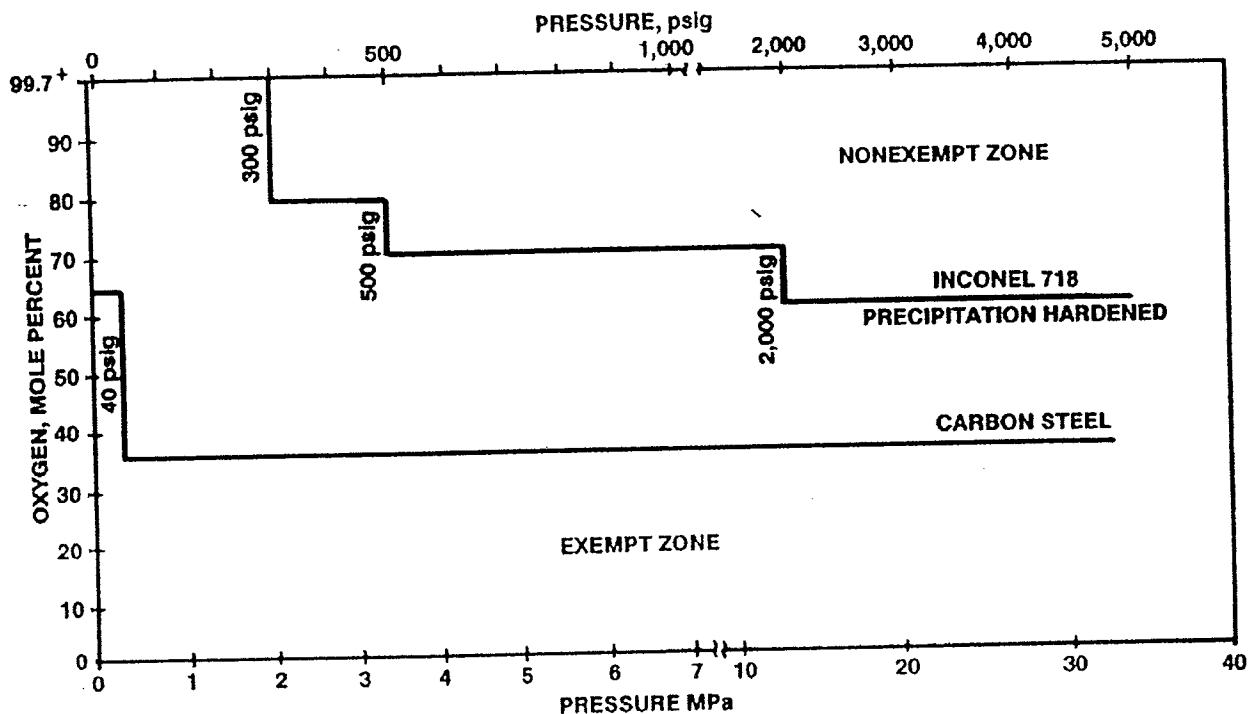


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- NOTES:
1. The maximum allowable velocity at impingement points is one-half the curve values.
 2. The maximum allowable temperature of some materials (e.g., aluminum alloys) may be limited by other considerations.
- English Units: $V_{MAX} \text{ (with 100 micron filter)} = 30.0 - 0.00125 (P-1000)$
 $V_{MAX} \text{ (without filter)} = 45.9 - 0.0051 P - 0.081 T + 0.000009 P \times T$
Where: $T = \text{Temperature, } ^\circ\text{F (150 to 400°F)}$
 $V_{MAX} = \text{Maximum allowable velocity, ft/s}$
 $P = \text{Pressure, PSIG (1000 to 5000 PSIG range)}$
- Metric Units: $V_{MAX} \text{ (with 100 micron filter)} = 9.53 - 0.055 (P-7)$
 $V_{MAX} \text{ (without filter)} = 13.20 - 0.213P - 0.044T + 0.00072 P \times T, \text{ m/s}$
Where: $T = \text{Temperature (66 to 205°C)}$
 $V_{MAX} = \text{Maximum allowable velocity, m/s}$
 $P = \text{Pressure, 7.0 to 34.6 MPa}$
- Example: For a pressure of 14 MPa and temperature of 205°C
 $V_{MAX} \text{ (without filter)} = 13.20 - 0.213(14) - 0.044 (205) + 0.00072(14 \times 205)$
= 3.264 m/s

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 3

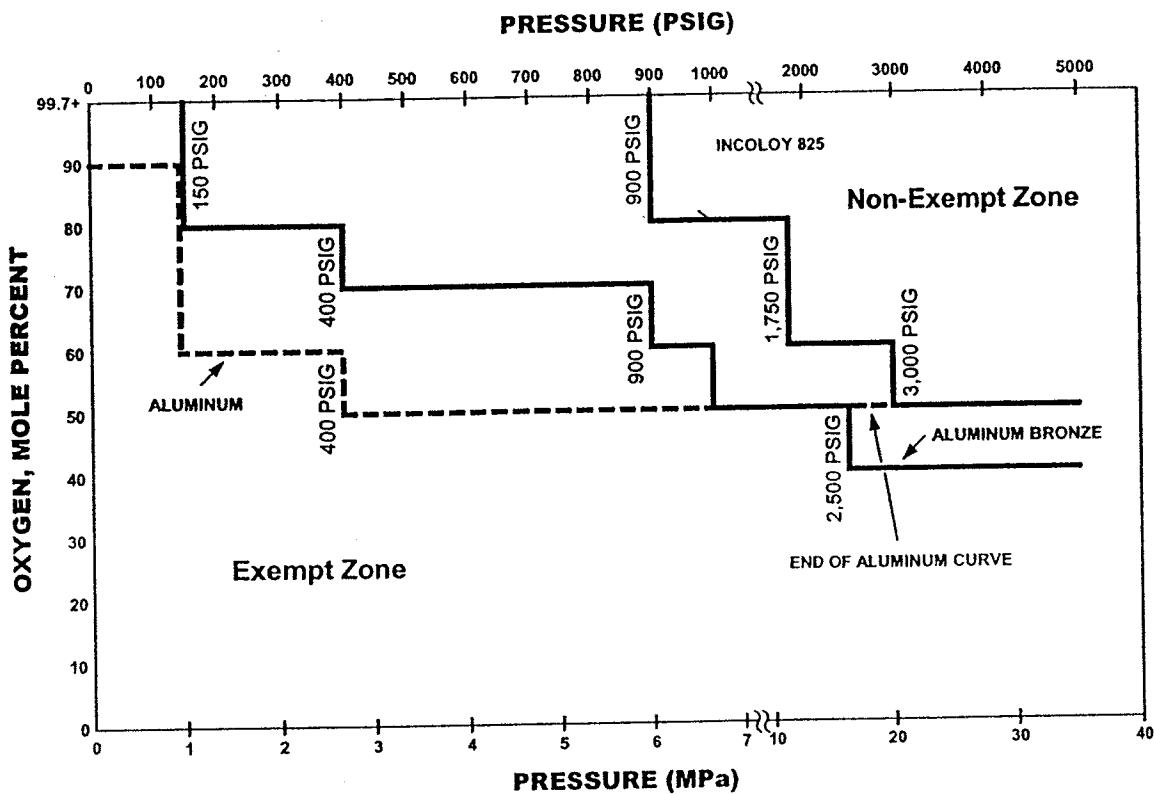
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
Carbon Steel and Inconel 718 Alloys

CONVERSION

PSIG	MPa
40	0.38
300	2.17
500	3.55
2000	13.9

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 4

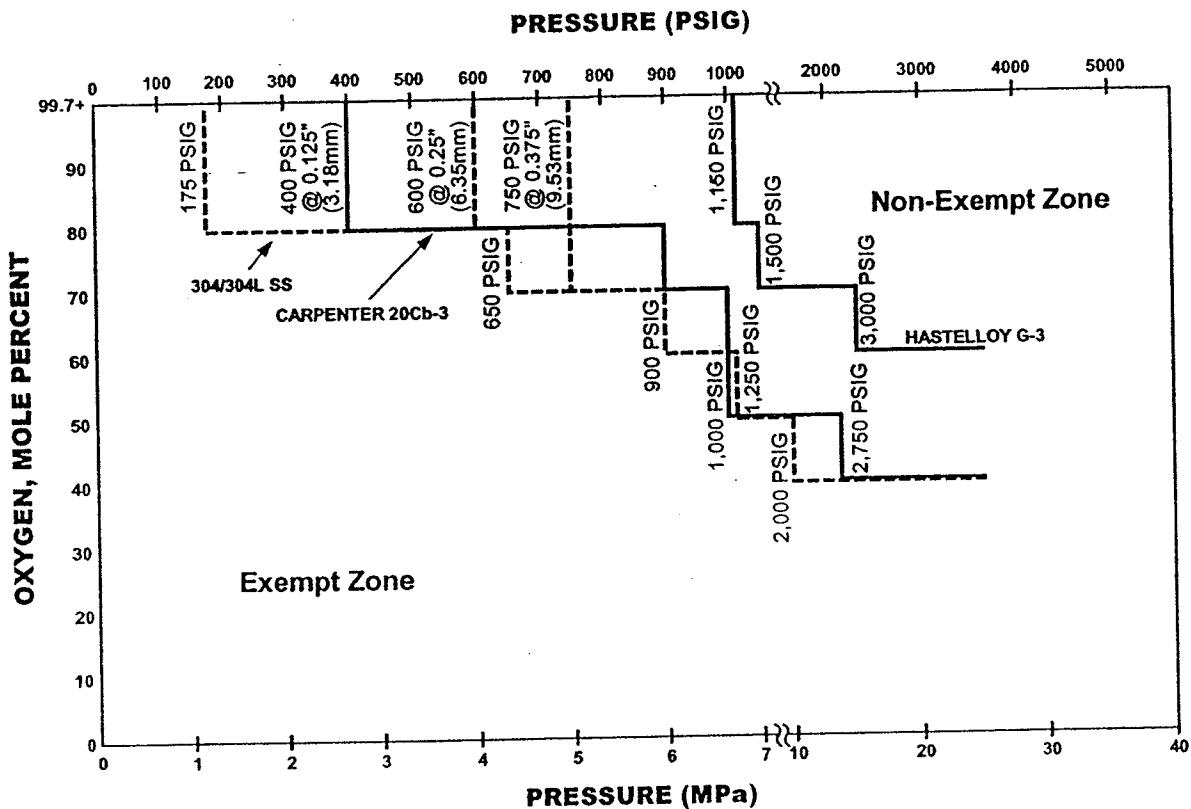
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
Aluminum, Aluminum Bronze and Incoloy 825 Alloys

CONVERSION

PSIG	MPa
150	1.14
400	2.86
900	6.31
1750	12.2
2500	17.3
3000	20.8

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 5

Maximum Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
304/304L Stainless Steel, Carpenter 20Cb-3, Hastelloy G-3 Alloys



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CONVERSION

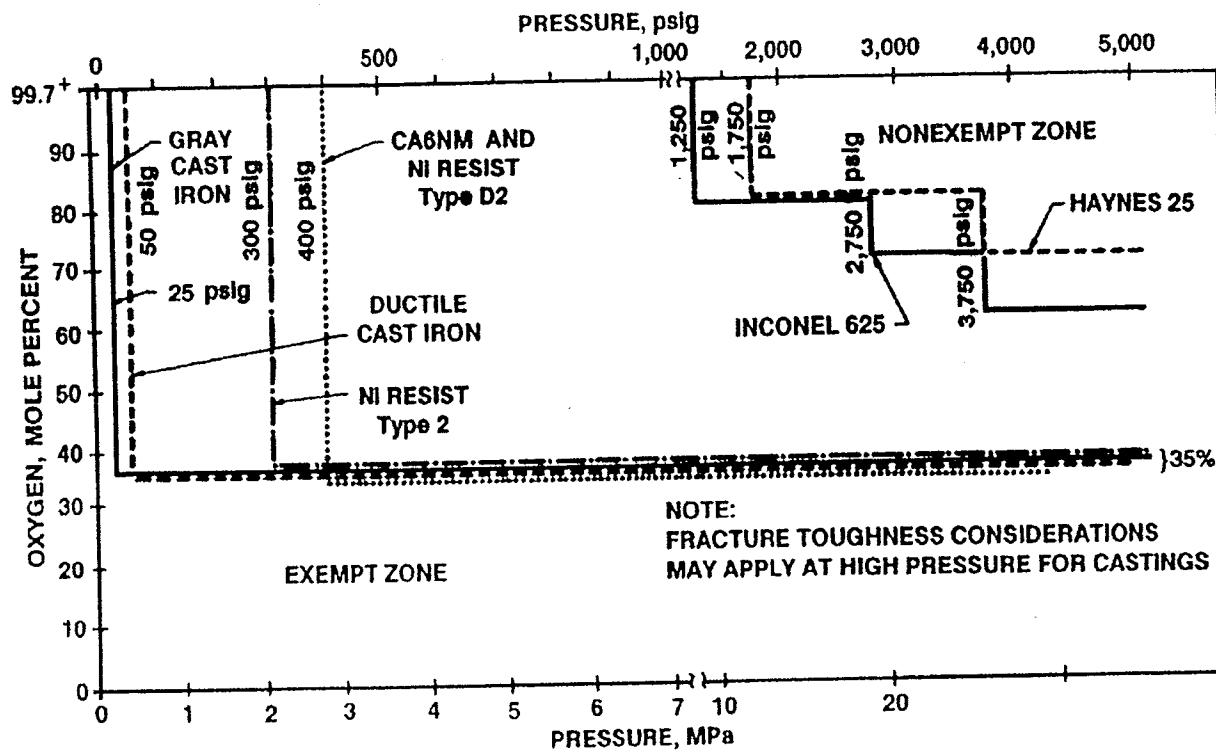
PSIG	MPa
175	1.31
400	2.86
600	4.24
650	4.58
750	5.27
900	6.31
1000	7.0

PSIG	MPa
1150	8.03
1250	8.72
1500	10.4
2000	13.9
2750	19.1
3000	20.8

Praxair Standard EN-6 (Rev. 2/20/02)

FIGURE 6

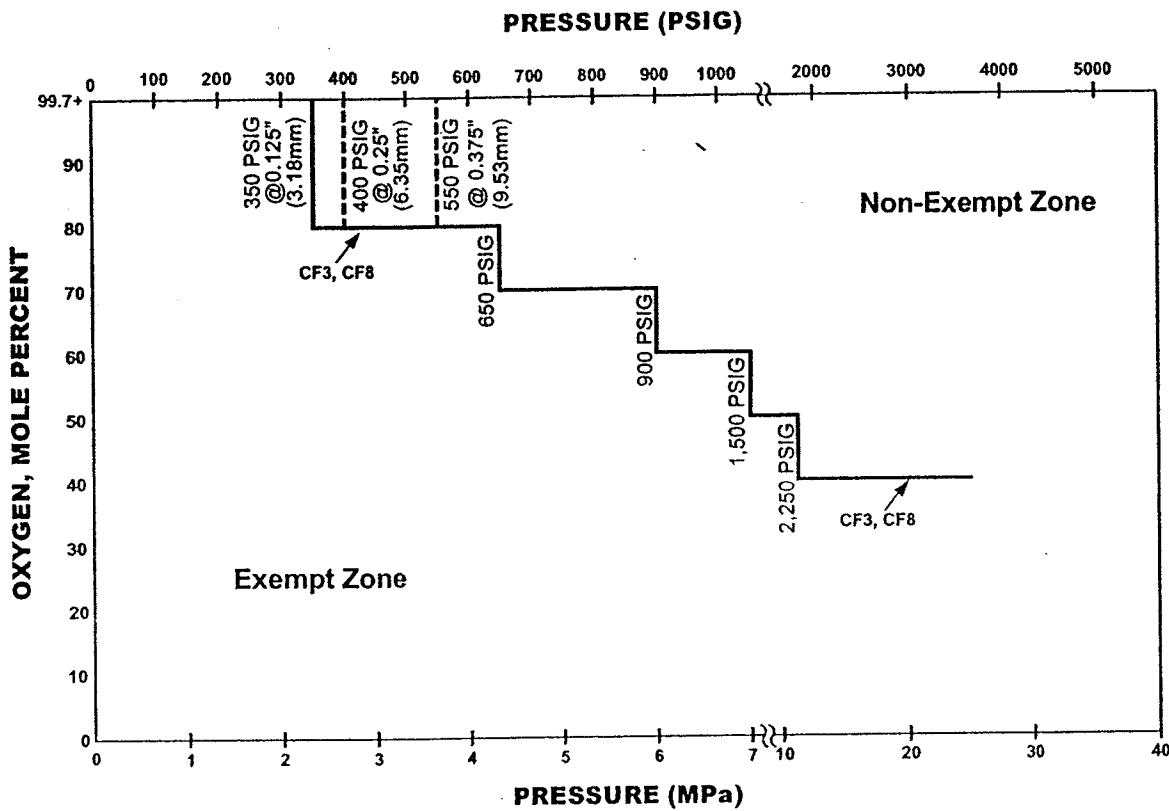
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38, 0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature, Gray Cast Iron, Ductile Cast Iron, Ni Resist Type 2, CA6NM Alloy, Ni Resist Type D2, Inconel 625 and Haynes 25

CONVERSION

PSIG	MPa
25	0.27
50	0.45
300	2.17
400	2.86
1250	8.72
1750	12.2
2750	19.1
3750	26.0

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 7

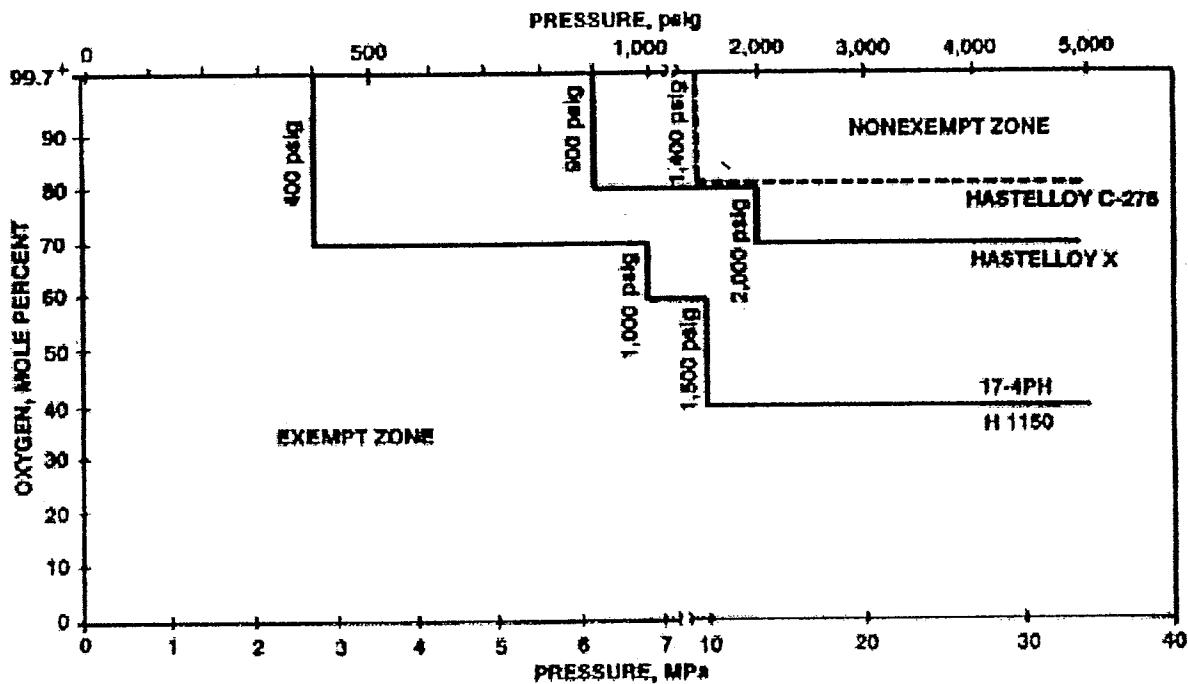
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38, 0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature, CF3, CF8, Cast Austenitic Stainless Steels at Thickness of 0.125 Inch (3.18 mm), 0.250 Inch (6.35 mm), and 0.375 Inch (9.53 mm)

CONVERSION

PSIG	MPa
350	2.51
400	2.86
550	3.89
650	4.58
900	6.31
1,500	10.4
2,250	15.6

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 8

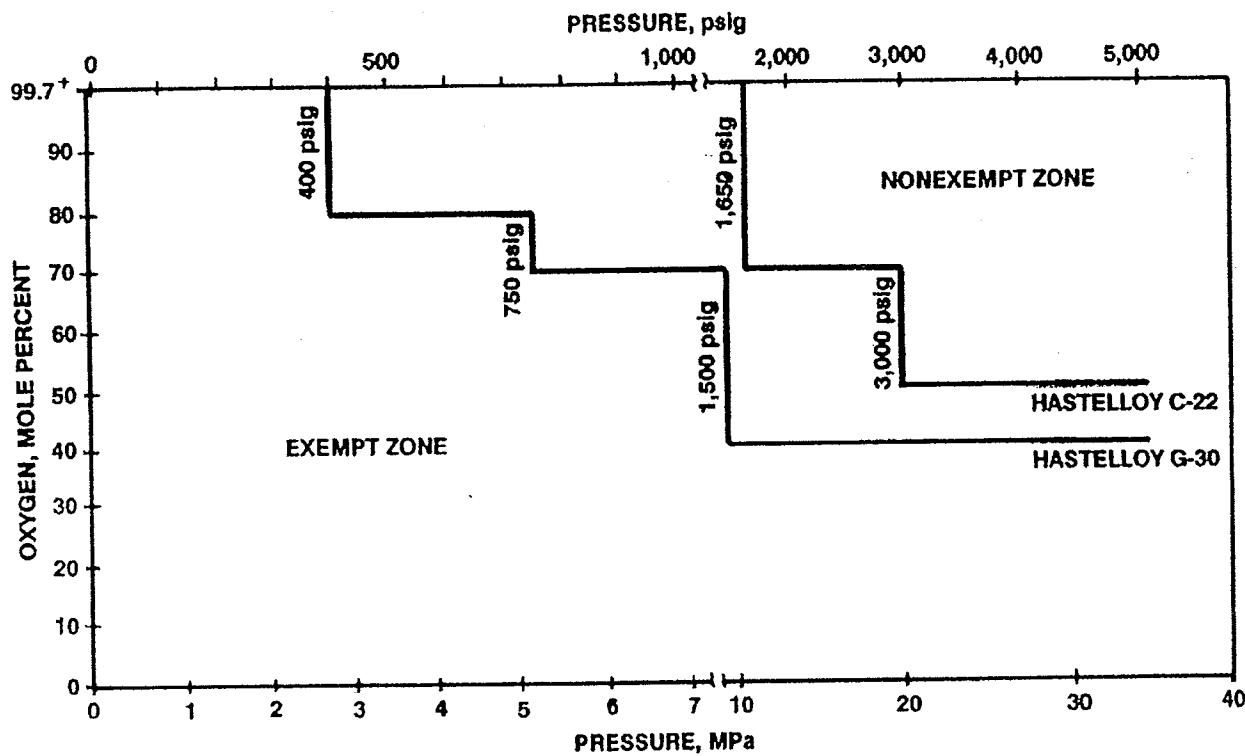
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
17-4PH (H 1150) Stainless Steel, Hastelloy C-276 and Hastelloy X Alloys

CONVERSION

PSIG	MPa
400	2.86
900	6.31
1000	7.0
1400	9.8
1500	10.4
2000	13.9

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 9

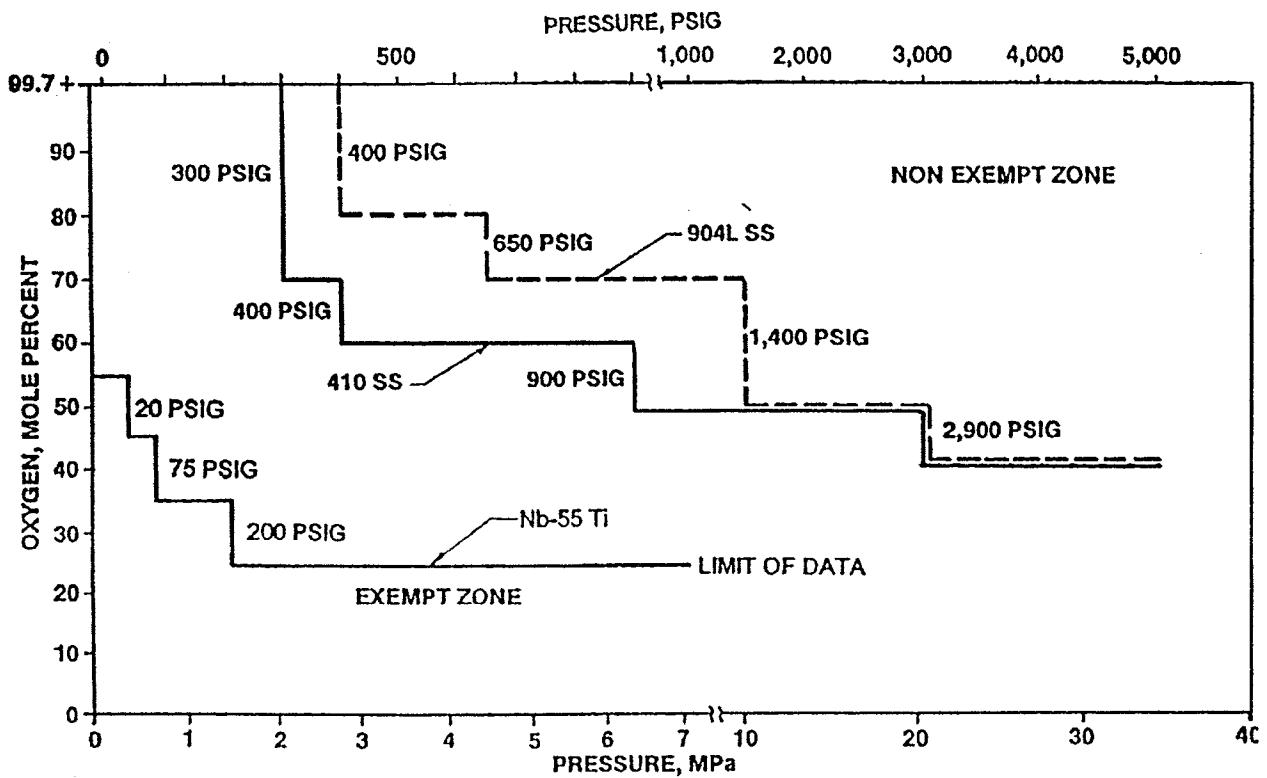
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
Hastelloy C-22 and Hastelloy G-30 Alloys

CONVERSION

PSIG	MPa
400	2.86
750	5.27
1500	10.4
1650	11.5
3000	20.8

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 10

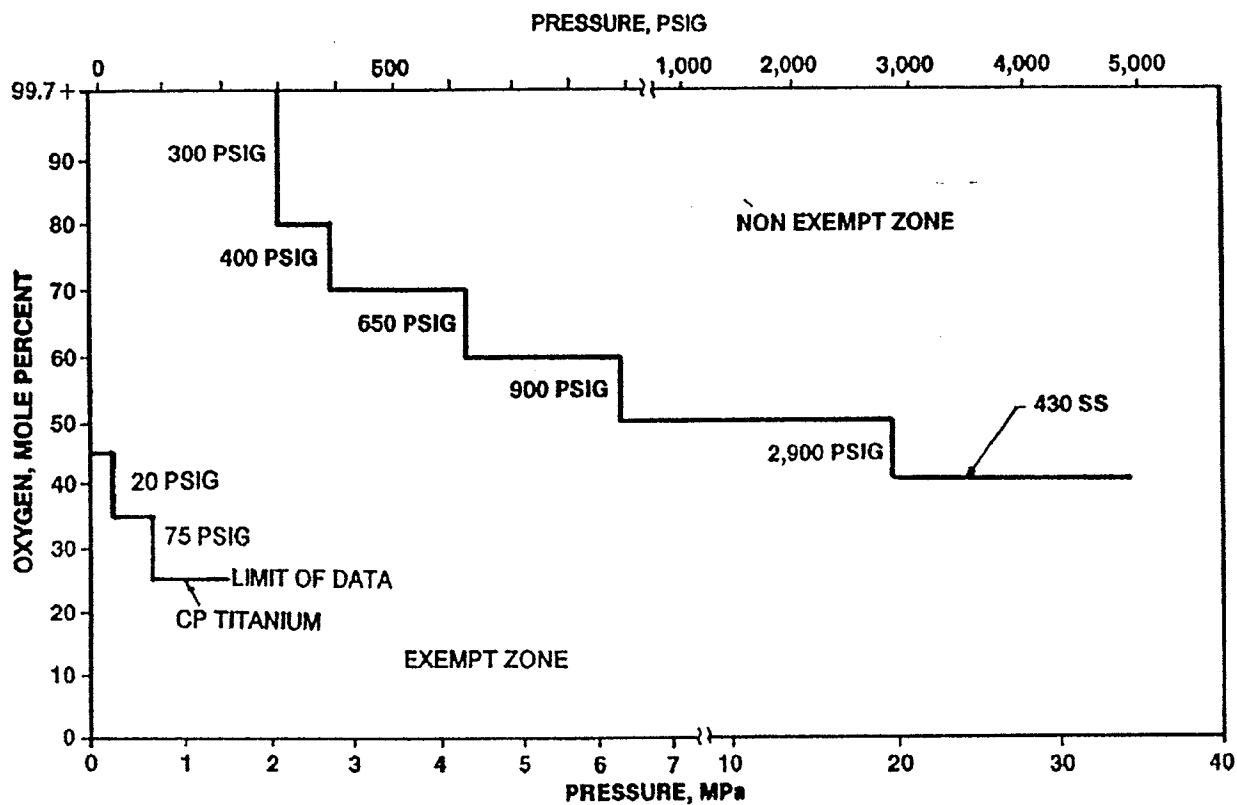
Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
410 Stainless Steel, 904L Stainless Steel and Titanium Alloy Nb-55Ti

CONVERSION

PSIG	MPa
20	0.24
75	0.62
200	1.48
300	2.17
400	2.86
650	4.58
900	6.31
1400	9.8
2900	20.1

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 11

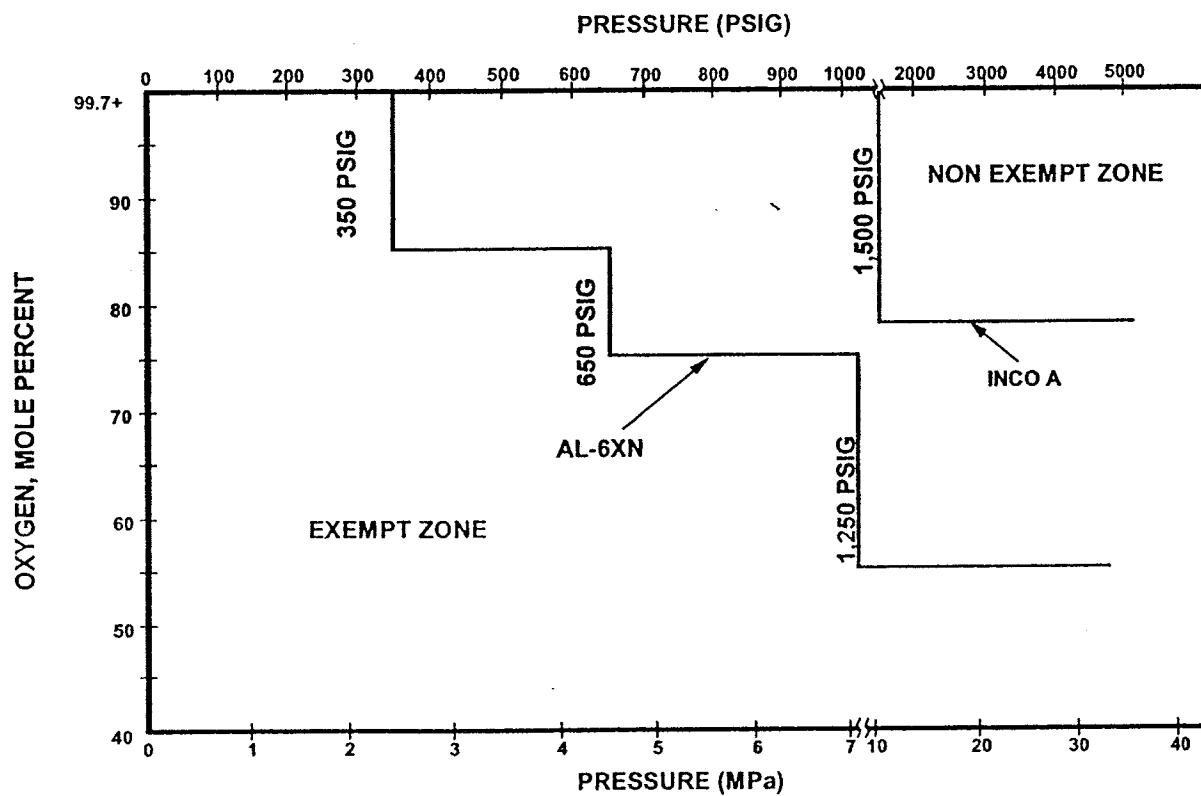
Material Velocity Exemption Curve for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
430 Stainless Steel and Commercially Pure (CP) Titanium

CONVERSION

PSIG	MPa
20	0.24
75	0.62
300	2.17
400	2.86
650	4.58
900	6.31
2900	20.1

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 12

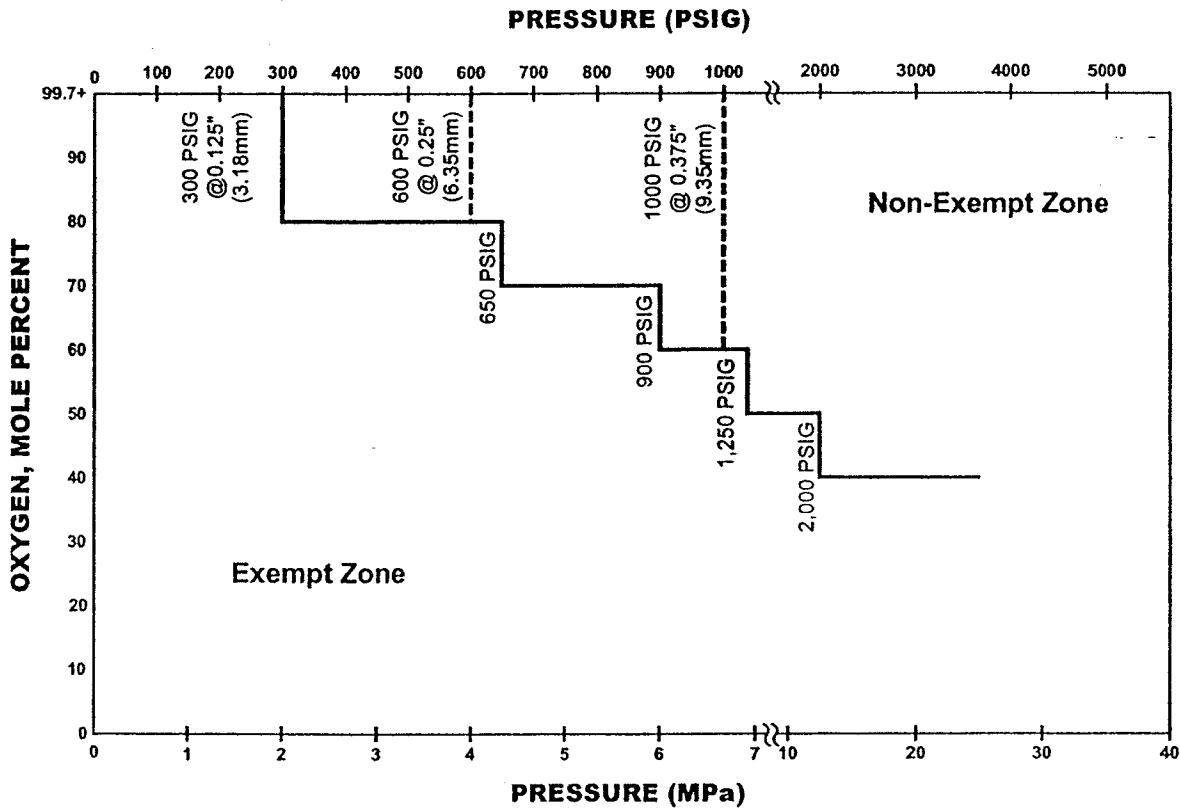
Material Velocity Exemption Curve for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature,
AL6XN and INCO A

CONVERSION

PSIG	MPa
350	2.51
650	4.58
1250	8.72
1500	10.4

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 13

Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
0.125 Inch (3.18 mm) Minimum Thickness and 400°F (205°C) Maximum Allowable Temperature
316/316L Stainless Steel at Thickness of 0.125 Inch (3.18 mm), 0.250 Inch (6.35 mm),
and 0.375 Inch (9.53 mm)

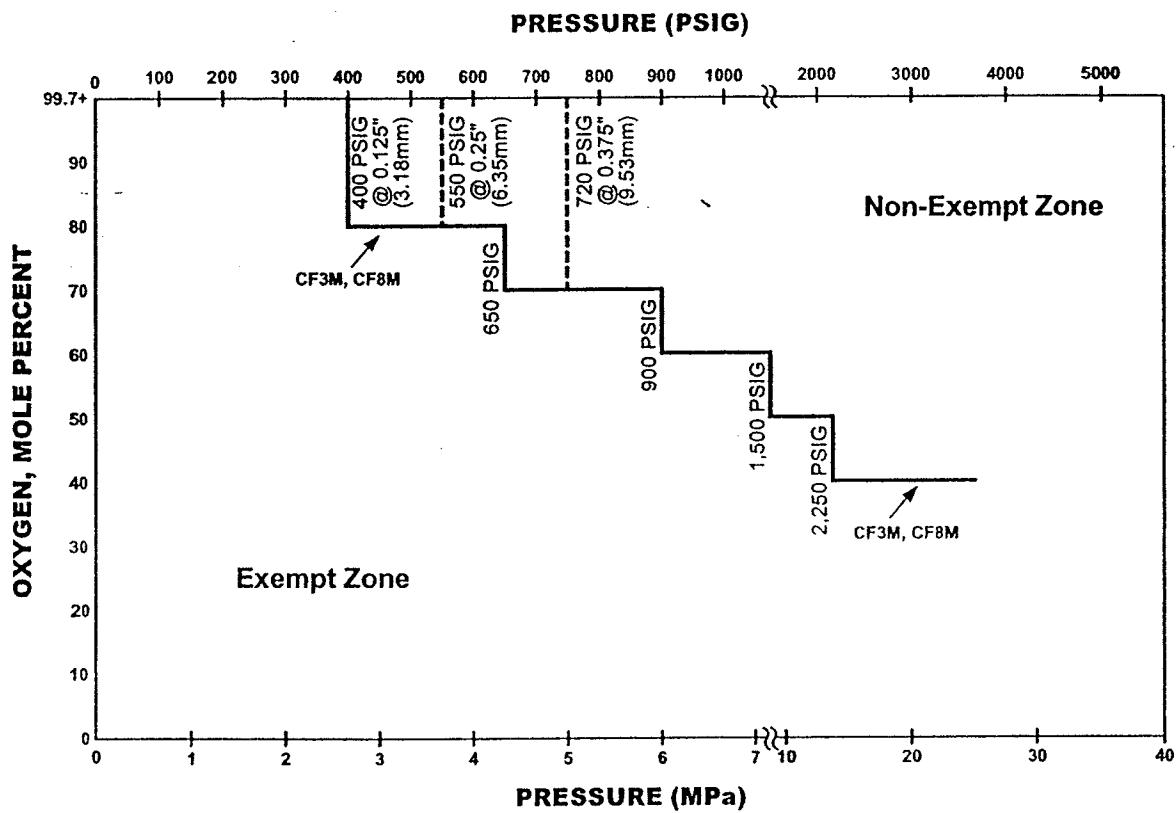
CONVERSION

PSIG	MPa
300	2.17
600	4.24
650	4.58
900	6.31
1000	7.00
1250	8.72
2000	13.9

CONFIDENTIAL

Praxair Standard EN-6 (Rev. 2/20/02)FIGURE 14

Material Velocity Exemption Curves for Systems Cleaned to Praxair Standard GS-38,
400°F (205°C) Maximum Allowable Temperature,
CF3M and CF8M Cast Austenitic Stainless Steels



98004-04

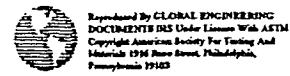
CONVERSION

PSIG	MPa
400	2.86
550	3.89
650	4.58
720	5.07
900	6.31
1500	10.4
2250	15.6

EXHIBIT 64



Designation: G 94 - 92

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Standard Guide for Evaluating Metals for Oxygen Service¹

This standard is issued under the fixed designation G 94; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide applies to metallic materials under consideration for oxygen or oxygen-enriched fluid service, direct or indirect, as defined in Section 3. It is concerned primarily with the properties of a material associated with its relative susceptibility to ignition and propagation of combustion. It does not involve mechanical properties, potential toxicity, outgassing, reactions between various materials in the system, functional reliability, or performance characteristics such as aging, shredding, or sloughing of particles, except when these might contribute to an ignition.

1.2 This document applies only to metals; nonmetals are covered in Guide G 63.

NOTE 1—The American Society for Testing and Materials takes no position respecting the validity of any evaluation methods asserted in connection with any item mentioned in this guide. Users of this guide are expressly advised that determination of the validity of any such evaluation methods and data and the risk of use of such evaluation methods and data are entirely their own responsibility.

NOTE 2—In evaluating materials, any mixture with oxygen exceeding atmospheric concentration at pressures higher than atmospheric should be evaluated from the hazard point of view for possible significant increase in material combustibility.

1.3 The values stated in SI units are to be regarded as the standard.

1.4 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

- D 2015 Test Method for Gross Calorific Value of Coal and Coke by the Adiabatic Bomb Calorimeter²
- D 2382 Test Method for Heat of Combustion of Hydrocarbon Fuels by Bomb Calorimeter (High-Precision Method)³
- D 2512 Test Method for Compatibility of Materials with Liquid Oxygen (Impact Sensitivity Threshold and Pass-Fail Technique)⁴

¹ This guide is under the jurisdiction of ASTM Committee G-4 on Compatibility and Sensitivity of Materials in Oxygen Enriched Atmospheres and is the direct responsibility of Subcommittee G04.02 on Recommended Practices.

Current edition approved July 15, 1992. Published September 1992. Originally published as G 94 - 87. Last previous edition G 94 - 90.

² Annual Book of ASTM Standards, Vol 05.05.

³ Annual Book of ASTM Standards, Vol 05.02.

⁴ Annual Book of ASTM Standards, Vol 15.03.

D 2863 Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)⁵

D 4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Intermediate Precision Method)⁶

G 63 Guide for Evaluating Nonmetallic Materials for Oxygen Service⁷

G 72 Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment⁷

G 86 Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments⁷

G 88 Guide for Designing Systems for Oxygen Service⁷

2.2 Compressed Gas Association Document:

Pamphlet G-4.4, Industrial Practices for Gaseous Oxygen Transmission and Distribution Piping Systems⁸

2.3 Adjunct:

Test Program Report on the Ignition and Combustion of Materials in High-Pressure Oxygen⁹

3. Terminology

3.1 Definitions:

3.1.1 *direct oxygen service*—in contact with oxygen during normal operations. Examples: oxygen compressor piston rings, control valve seats (see Guide G 63).

3.1.2 *impact-ignition resistance*—the resistance of a material to ignition when struck by an object in an oxygen atmosphere under a specific test procedure (see Guide G 63).

3.1.3 *indirect oxygen service*—not normally in contact with oxygen, but which might be as a result of a reasonably foreseeable malfunction, operator error, or process disturbance. Examples: liquid oxygen tank insulation, liquid oxygen pump motor bearings (see Guide G 63).

3.1.4 *maximum use pressure*—the maximum pressure to which a material can be subjected due to a reasonably foreseeable malfunction, operator error, or process upset (see Guide G 63).

3.1.5 *maximum use temperature*—the maximum temperature to which a material can be subjected due to a reasonably foreseeable malfunction, operator error, or process upset (see Guide G 63).

3.1.6 *nonmetallic*—any material, other than a metal, or any composite in which the metal is not the most easily

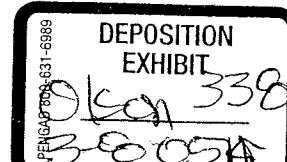
⁵ Annual Book of ASTM Standards, Vol 08.02.

⁶ Annual Book of ASTM Standards, Vol 05.03.

⁷ Annual Book of ASTM Standards, Vol 14.02.

⁸ Available from Compressed Gas Association, Inc., 1235 Jefferson Davis Highway, Arlington, VA.

⁹ Available from ASTM Headquarters, Order PCN Number 12-700940-31.



G 94

ignited component and for which the individual constituents cannot be evaluated independently (see Guide G 63).

3.1.7 *operating pressure*—the pressure expected under normal operating conditions (see Guide G 63).

3.1.8 *operating temperature*—the temperature expected under normal operating conditions (see Guide G 63).

3.1.9 *oxygen-enriched*—applies to a fluid (gas or liquid) that contains more than 25 mol % oxygen (see Guide G 63).

3.1.10 *qualified technical personnel*—persons such as engineers and chemists who, by virtue of education, training, or experience, know how to apply physical and chemical principles involved in the reactions between oxygen and other materials (see Guide G 63).

3.1.11 *reaction effect*—the personnel injury, facility damage, product loss, downtime, or mission loss that could occur as the result of an ignition (see Guide G 63).

3.2 Description of Term Specific to this Standard:

3.2.1 *autoignition temperature*—the lowest temperature at which a material will spontaneously ignite in oxygen under specific test conditions.

4. Significance and Use

4.1 The purpose of this guide is to furnish qualified technical personnel with pertinent information for use in selecting metals for oxygen service in order to minimize the probability of ignition and the risk of explosion or fire. It is intended for use in selecting materials for applications in connection with the production, storage, transportation, distribution, or use of oxygen. *It is not intended as a specification for approving materials for oxygen service.*

5. Factors Affecting Selection of Material

5.1 General:

5.1.1 The selection of a material for use with oxygen or oxygen-enriched atmospheres is primarily a matter of understanding the circumstances that cause oxygen to react with the material. Most materials in contact with oxygen will not ignite without a source of ignition energy. When an energy-input exceeds the configuration-dependent threshold, then ignition and combustion may occur. Thus, the materials' flammability properties and the ignition energy sources within a system must be considered. These should be viewed in the context of the entire system design so that the specific factors listed in this guide will assume the proper relative significance. To summarize: it depends on the application.

5.2 Relative Amount of Data Available for Metals and Nonmetals:

5.2.1 Studies of the flammability of gaseous fuels were begun more than 150 years ago. To date, an extremely wide variety of applications have been studied and documented, including a wide range of important subtleties such as quenching phenomena, turbulence, cool flames, influence of initial temperature, etc., all of which have been used effectively for safety and loss prevention. A smaller, yet still substantial, background exists for nonmetallic solids. In contrast to this, the study of the flammability of metals dates only to the 1950's, and even though it has accelerated rapidly, the uncovering and understanding of subtleties have not yet matured. In addition, the heterogeneity of the metal and oxidizer systems and the heat transfer properties of metals, as well as the known, complex ignition energy and ignition/burning

mechanisms, clearly dictate that caution is required when applying laboratory findings to actual applications. In many cases, laboratory metals burning tests are designed on what is believed to be a worst-case basis, but could the particular actual application be worse? Further, because so many subtleties exist, accumulation of favorable experience (no metal fires) in some particular application may not be as fully relevant to another application as might be the case for gaseous or nonmetallic solids where the relevance may be more thoroughly understood.

5.3 Relationship of Guide G 94 with Guides G 63 and G 88:

5.3.1 This guide addresses the evaluation of metals for use in oxygen systems and especially in major structural portions of a system. Guide G 63 addresses the evaluation of nonmetals. Guide G 88 presents design and operational maxims for all systems. In general, however, Guides G 63 and G 88 focus on physically small portions of an oxygen system that represent the critical sites most likely to encounter ignition.

5.3.2 The nonmetals in an oxygen system (valve seats and packing, piston rings, gaskets, o-rings) are small; therefore, the use of the most fire-resistant materials is usually a realistic, practical option with regard to cost and availability. In comparison, the choice of material for the major structural members of a system is much more limited, and the use of special alloys may have to be avoided to achieve realistic costs and delivery times. Indeed, with the exception of ceramic materials, which have relatively few practical uses, most nonmetals have less fire resistance than virtually all metals. Since nonmetals are typically introduced into a system to provide a physical property not achievable from metals, and since nonmetals may serve as "links" in a kindling chain (see 5.6.5), and since the locations of use are typically mechanically severe, the primary thrust in achieving compatible oxygen systems rests with the minor components as addressed by Guides G 63 and G 88 that explain the emphasis on using the most fire-resistant materials.

5.3.3 Since metals are typically more fire-resistant and are used in typically less fire-prone functions, they represent a second tier of interest. However, because metal components are relatively so large, a fire of a metal component is a very important event, and should a nonmetal ignite, any consequential reaction of the metal can aggravate the severity of an ignition many times over. Hence, while the selection of nonmetals by Guide G 63 and the careful design of components by Guide G 88 are the first line of defense, optimum metal selection is an important second-line of defense.

5.4 Differences in Oxygen Compatibility of Metals and Nonmetals:

5.4.1 There are several fundamental differences between the oxygen compatibility of metals and nonceramic nonmet-

TABLE 1 Comparison of Metals and Nonmetals Flammability

	Metals	Nonmetals
Combustion products	molten metal oxide	hot gases
Autoignition temperatures	900–2000°C	150–500°C
Thermal conductivities	higher	lower
Flame temperature	higher	lower
Heat release	higher due to density	lower
Surface oxide	can be protective	negligible

als. These principal differences are summarized in Table 1.

5.4.2 Common-use metals are harder to ignite. They have high autoignition temperatures in the range 900 to 2000°C (1650 to 3600°F). In comparison, most combustible nonmetals have autoignition temperatures in the range 150 to 500°C (300 to 1000°F). Metals have high thermal conductivities that help dissipate local heat inputs that might easily ignite nonmetals. Many metals also grow protective oxide coatings (see 5.5) that interfere with ignition and propagation.

5.4.3 Once ignited, however, metal combustion can be highly destructive. Adiabatic flame temperatures for metals are much higher than for most polymers (Table X1.7). The greater density of most metals provides greater heat release potential from components of comparable size. Since many metal oxides do not exist as oxide vapors (they largely dissociate upon vaporization), combustion of these metals inherently yields coalescing liquid metal oxide of high heat capacity in the flame zone at the oxide boiling point (there may be very little gaseous metal oxide). In comparison, combustion of polymers yields gaseous combustion products (typically carbon dioxide and steam) that tend to dissipate the heat release.

5.4.4 Contact with a mixture of liquid metal and oxide at high temperature results in a massive heat transfer relative to that possible upon contact with hot, low-heat-capacity, gaseous combustion products of polymers. As a result, metal combustion can be very destructive. Indeed, certain metal combustion flames are an effective scarifying agent for hard-to-cut materials like concrete (1).¹⁰

5.4.5 Finally, because most polymers produce largely inert gas combustion products, there is a substantial dilution of the oxygen in the flame that inhibits combustion and if in a stagnant system, may even extinguish a fire. For many metals, combustion produces the molten oxide of negligible volume condensing in the flame front and, hence, oxygen dilution is much less.

5.5 Protective Oxide Coatings:

5.5.1 Oxides that grow on the surfaces of metals can play a role in the metal's flammability. Those films that interfere with ignition and combustion are known as protective oxides. Typically, an oxide will tend to be protective if it fully covers the exposed metal, if it is tenaciously adherent, and if it has a high melting point. Designers have very limited control over the integrity of an oxide layer; however, since oxide can have significant influence on metal's test data, an understanding of its influence is useful.

5.5.2 A protective oxide provides a barrier between the metal and the oxygen. Hence, ignition and combustion can be inhibited in those cases where the oxide barrier is preserved. For example, in some cases, an oxide will prevent autogenous ignition of a metal up to the temperature at which the metal melts and produces geometry changes that breach the film. In other cases (such as anodized aluminum wires), the oxide may be sufficiently sturdy as either a structure or a flexible skin to contain and support the molten base metal at temperatures up to the melting point of the oxide itself. In either of these cases, however, autogenous

TABLE 2 Pilling and Bedworth Ratios^a of Metal Oxides

Nonprotective Oxides		Potentially Protective Oxides	
Oxide	P&B < 1	Oxide	P&B ≥ 1
BaO	0.685	Al ₂ O ₃	1.29
CaO	0.663–0.637	CuO	1.71–1.77
MgO	0.806	Cu ₂ O	1.68
		Cr ₂ O ₃	2.02
		FeO	1.78
		Fe ₂ O ₃	2.15
		Fe ₃ O ₄	2.09
		CoO	1.78
		MoO ₃	2.10
		NiO	1.70
		PbO	1.28–1.52
		SnO	1.15–1.28
		SnO ₂	1.19–1.33
		TiO ₂	1.76–1.95
		ZnO	1.59

^a The Pilling and Bedorth (P&B) ratio is the ratio of the volume of a metal oxide compared to the volume of metal from which it was grown. A P&B ratio ≥ 1 suggests the potential for an oxide to be protective if it is also conformal and tenaciously adherent. All data are calculated and do not always agree with P&B ratios in the literature (1–5).

ignition may result at much lower temperatures if the metal experiences mechanisms that damage the oxide coating. Such oxide damaging mechanisms may be due to mechanical stresses, frictional rubs and abrasion, or chemical oxide attack (amalgamation, etc.). Depending upon the application, a high metal autoignition temperature, therefore, may be misleading relative to the metal's flammability.

5.5.3 One criterion for estimating whether an oxide is protective is based upon whether the oxide that grows on a metal occupies a volume greater or less than the volume of the metal it replaces. Pilling and Bedorth (2) formulated an equation for predicting the transition between protective and nonprotective oxides in 1923. Two forms of the Pilling and Bedorth (P&B) equation appear in the literature and can yield different results. ASTM Committee G-4 has concluded that the most meaningful formulation for the P&B ratio in oxide evaluations for flammability situations is:

$$\text{P\&B Ratio} = \frac{Wd}{awD},$$

where the metal, M, forms the oxide $\text{M}_{a,b}\text{O}_b$, a and b are the oxide stoichiometry coefficients, W is the formula weight of the oxide, d is the density of the metal, w is the formula weight of the metal, and D is the density of the oxide. The other form of the equation treats the stoichiometry coefficient as unity and thus for those oxides that have a single metal atom in the formula, the two equations yield the same results. Pilling and Bedorth ratios should always reference an oxide rather than the metal of oxide origin, because for many metals, several different oxides can form each having a different P&B ratio. For example, normal atmospheric corrosion of iron tends to produce the oxide, Fe_2O_3 , whereas the oxide that forms for iron at the elevated temperatures of combustion is Fe_3O_4 . In cases where a mixture of oxides forms, the stoichiometry coefficients, a and b, may be weighted to reflect this fact. Table 2 presents numerous P&B ratios for a number of metal oxides. The P&B ratio suggests whether a grown metal oxide is sufficient in volume to thoroughly cover a metal surface, but it does not provide insight into the tenacity of the coating or whether it does indeed grow in a conformal fashion. The ratios in Table 2 have been segregated into those oxides that one would

¹⁰ The boldface numbers in parentheses refer to the list of references at the end of this guide.

suspect to be nonprotective ($P \& B < 1$) and those that might more likely be protective ($P \& B \geq 1$). Note also that if the P&B ratio $>> 1$ (as in the case of Fe_2O_3) the volume of the oxide can increase so dramatically that chipping, cracking or breaking can occur that may reduce its "protection." The effect of protective oxides on alloys is a still more complex aspect of a metals flammability.

5.6 Operational Hazard Thresholds:

5.6.1 Most practical oxygen systems are capable of ignition and combustion to some extent under at least some conditions of pressure, temperature, flow, etc. The key to specifying oxygen-compatible systems is avoiding the circumstances in which ignition is likely and in which consequential combustion may be extensive. This often involves avoiding the crossing of hazard thresholds.

5.6.2 For example, many materials exhibit a bulk system-related ignition temperature that represents a hazard threshold. When a region of a system is exposed to a temperature greater than its bulk in-situ autoignition temperature, the likelihood of an ignition increases greatly; a hazard threshold has been crossed.

5.6.3 Hazard thresholds can be of many types. Ignition may depend upon a minimum heat energy input, and the threshold may be different for heat inputs due to heat transfer, friction, arc/spark, etc. Propagation may require the presence of a minimum oxygen concentration (the oxygen index is one such flammability limit) or it may require a minimum oxygen pressure (a threshold pressure below which propagation does not even occur in pure oxygen). It may also require a specific geometry.

5.6.4 For a fire to occur, it may be necessary to cross several thresholds of hazard simultaneously. For example, brief local exposure to high temperature above the ignition temperature might not produce ignition unless the heat transferred also exceeds the minimum energy threshold. And even if a local ignition results, the fire may self-extinguish without propagation if the pressure, oxidant concentration, or other conditions, are not simultaneously in excess of their related hazard threshold. It is desirable to operate on the conservative side of as many hazard thresholds as possible.

5.6.5 *Kindling Chains*—A kindling chain reaction can lead to the crossing of a hazard threshold. In a kindling chain, ignition of an easily ignited material (such as a contaminant by adiabatic compression) may not release enough heat to, in turn, ignite a valve body, but may be sufficient to ignite a valve seat, which, in turn, may release sufficient heat to ignite the larger, harder-to-ignite valve body.

5.7 Practical Metal Systems:

5.7.1 It is not always possible to use the most fire-resistant metals in practical systems. As a result, operation below every hazard threshold may not always be used to minimize the chance of a fire. In this case, additional conservatism is often used to increase the safety margins where possible. For example, if the pressure and temperature of an application are such that particle impact may cause an ignition, the remedy has been to limit the severity of particle impacts by limiting gas velocity and filtering or screening of particles. This, in effect, limits the application severity by constraining the operation conditions; CGA Pamphlet G-4.4 details an industry practice using this approach.

5.8 Properties of the Metal:

5.8.1 *Ease of Ignition*—Although metals are typically harder to ignite than nonmetals, there is a wide range of ignition properties exhibited among potential structural materials, and, indeed, some metals are difficult to ignite in some ways while being relatively easy to ignite in others. The principal recognized sources of metal ignition include:

5.8.1.1 Contaminant promotion where the contaminant itself may be ignited by mechanical impact, adiabatic compression, sparks, or resonance.

5.8.1.2 Particle impact ignition where a particle may ignite and promote ignition of the metal.

5.8.1.3 Friction ignition where the friction results from mechanical failure, cavitation, rubs, etc.

5.8.1.4 Bulk heating to ignition.

5.8.2 Ignition may also result from the following mechanisms, though these are not thoroughly studied nor understood for metals, nor have they been implicated in significant numbers of incidents relative to those in 5.8.

5.8.2.1 Mechanical impact.

5.8.2.2 Resonance.

5.8.2.3 Fresh metal exposure.

5.8.2.4 Crack propagation.

5.8.2.5 Electric arc or spark.

5.8.2.6 Puncture.

5.8.2.7 Trapped volume pressurization.

5.8.2.8 In many of these mechanisms, heating to the autoignition temperature can result. For some of them, the achievement of ignition also can result from the material self heating as the freshly exposed metal oxidizes and releases heat.

5.8.3 Ignition can result from bulk heating to the autoignition temperature, but this is rare in oxygen systems unless an environmental fire is present or unless electrical heaters experience runaways. Autoignition temperatures are often used to compare metals, but they can yield rankings that disagree with observed experience. This is because ignition is a very complex process. For example, where a metal grows a protective oxide, the autoignition temperature can vary widely depending upon such things as the adherence of the oxide, its degree of protection (as indicated in part by its Pilling and Bedworth number), and its melting point.

5.8.4 *Properties and Conditions Affecting Potential Resultant Damage*—A material's heat of combustion, its mass, the oxygen concentration, the flow conditions before and after ignition, and the flame propagation characteristics affect the potential damage if ignition should occur. They should be taken into account in estimating the reaction effect in 8.5. Since so much damage in metal fires is attributable to direct contact with the molten oxide and from radiation due to its extremely high temperature, the probable flow path or trajectory of the molten oxide should be considered in predicting the zones of greatest damage.

5.9 Extenuating Factors:

5.9.1 In choosing major structural members of a system, practicality becomes a critical factor. Frequently, the more fire-resistant materials are simply impractical or uneconomical. For example, their strength-to-weight ratios may not meet minimum mechanical standards for turbine wheels. The cost or availability of an alloy may also preclude its use in a long pipeline. Corrosive environments may preclude still other materials. In contrast, there may be a base of experience

with traditional metals in oxygen service, such as carbon steel pipelines, that clearly demonstrates suitability for continued service with appropriate safeguards. As a result, where these extenuating factors are present, less than optimum metals are frequently selected in conjunction with operational controls (such as operating valves only during zero-flow), established past practice (such as CGA Pamphlet G-4.4 for steel piping), or measures to mitigate the risk (such as use with a shield or removal of personnel from the vicinity).

5.10 Operating Conditions:

5.10.1 Conditions that affect the suitability of a material include the other materials of construction and their arrangement and geometry in the equipment and also the pressure, temperature, concentration, flow, and velocity of the oxygen. For metals, pressure, concentration or purity, and oxygen flow rate are usually the most significant factors. Temperature is a much less significant factor than is the case for nonmetals because ignition temperatures of metals are all significantly higher than those of nonmetals. The effects of these factors show up in the estimate of ignition potential (8.2) and reaction effect assessment (8.5), as explained in Section 8.

5.10.2 *Pressure*—The oxygen pressure is important, because it generally affects the generation of potential ignition mechanisms, and because it affects the destructive effects if ignition should occur. While generalizations are difficult, rough scales would be as given in Table 3.

NOTE 3—While the pressure generally affects the reaction as given in Table 3, data indicate that it has varying effects on individual flammability properties. For example, for many metals, increasing pressure results in the following:

- (a) A reduction in the oxygen concentration required to enable propagation;
- (b) Differing effects on autoignition temperature, with many metals having invariant autoignition temperatures, many metals having decreasing autoignition temperatures, and some metals having increasing autoignition temperatures;
- (c) An increase in sensitivity to mechanical impact;
- (d) A negligible change in heat of combustion;
- (e) An increase in the difficulty of friction ignition, apparently due to increased convective heat dissipation;
- (f) An increase in the likelihood of adiabatic compression ignition, however, adiabatic compression is an unlikely direct ignition mechanism for metals except at pressures in excess of 20 000 kPa (3 000 psi); and
- (g) An increase in the rate of combustion.

5.10.3 *Concentration*—As oxygen concentration decreases from 100 %, the likelihood and intensity of a potential fire also decrease. Therefore, greater latitude may be exercised in the selection of materials. For all metals, there is an oxygen concentration (a flammability limit analogous to the oxygen index), below which (in the specific metal combustion tests undertaken) propagating combustion will not occur, even in the presence of an assured (very high energy) ignition. This

concentration decreases with increasing pressure above a threshold pressure (below which the metal will not burn even in pure oxygen). The concentration may approach an asymptote at high pressures, Fig. X1.1.

NOTE 4—Some metals are extremely sensitive to oxygen purity. Since many metal oxides do not exist as gases, the combustion products of some metals do not interfere with the combustion as is the case with polymers. Therefore, small amounts of inert gases in the oxygen can accumulate and control the combustion. In a research project, Benning et al. (6) found that as little as 0.2 % argon could increase the minimum pressure at which 6.4-mm (0.25-in.) diameter aluminum rods sustained combustion from 210 kPa (30 psi absolute) to 830 kPa (120 psi absolute). This effect is believed to be most significant for "vapor-burning" metals such as aluminum and less significant for "liquid-burning" metals such as iron. Theory is found in Benning (6) and Glassman (7-9).

5.10.4 *Flow and Oxygen Inventory*—The quantity of oxygen present and the rate at which it can flow to an ignition site affects the intensity and scale of a metal fire. Since many metals do not form gaseous combustion products, self extinguishment through accumulation of combustion products cannot occur as it does with polymers. However, accumulation of inert gases in the oxygen may cause extinguishment. Since the density of oxygen gas is much lower than the metal density, the quantity of metal that can burn is often limited by the quantity of oxygen present or the rate at which it can be supplied.

5.10.5 *Temperature*—Increasing temperature obviously increases the risk of ignition, as well as the prospect for sustained combustion. Indeed, an increase in temperature may enable combustion in cases where propagation would not be possible at lower temperature. The influence of environmental temperature on metals is much less significant than for nonmetals; this is because the autoignition temperature of the most sensitive bulk metal (perhaps carbon steel at ~900°C (~1650°F)) is significantly greater than for the most resistant polymers (for example PTFE at ~480°C (~900°F)).

5.10.5.1 Occasionally, traditional metals have been used at temperatures to 300°C (~570°F) without spontaneous ignition problems.

5.10.6 *Geometry*—The geometry of the component can have a striking effect on the flammability of metals. Generally, thin components or high-surface-area-to-volume components will tend to be more flammable. For example, both Stoltzfus et al (10) and Dunbobbin et al. (11) have shown that materials such as thin wire mesh and thin layered sheets can become much more flammable than might be expected on the basis of tests of rods. In these works, copper and brass alloys that typically resist propagation in bulkier systems were capable of complete combustion. Zabrenski et al. (12) have found that thin-wall tubes of 6.4-mm (0.25-in.) diameter stainless steel would propagate combustion at atmospheric pressure while solid rods required pressures of 5.0 MPa [740 psi absolute].

5.11 *Ignition Mechanisms*—For combustion to occur, it is necessary to have three elements present: oxidizer, fuel, and ignition energy. The oxygen environment is obviously the oxidizer, and the system itself is the fuel. Several potential sources of ignition energy are listed below. The list is not all-inclusive or in order of importance or in frequency of occurrence.

TABLE 3 Effect of Pressure on Typical Metal Burning Reactions

kPa	psi	Pressure Effect Assessment ^a
0-70	0-10	relatively mild
70-700	10-100	moderate
700-7000	100-1000	intermediate
7000-20 000	1000-3000	severe
Over 20 000	Over 3000	extremely severe

^a See 5.10.2.

TABLE 4 Reaction Effect Assessment for Oxygen Applications

Rating		Effect on Personnel Safety	Effect on System Objectives	Effect on Functional Capability
Code	Severity Level			
A	negligible	No injury to personnel.	No unacceptable effect on production, storage, transportation, distribution, or use as applicable.	No unacceptable damage to the system.
B	marginal	Personnel-injuring factors can be controlled by automatic devices, warning devices, or special operating procedures.	Production, storage, transportation, distribution, or use as applicable is possible by utilizing available redundant operational options.	No more than one component or subsystem damaged. This condition is either repairable or replaceable on site within an acceptable time frame.
C	critical	Personnel injured: (1) operating the system; (2) maintaining the system; or (3) being in vicinity of the system.	Production, storage, transportation, distribution, or use as applicable impaired seriously.	Two or more major subsystems are damaged; this condition requires extensive maintenance.
D	catastrophic	Personnel suffer death or multiple injuries.	Production, storage, transportation, distribution, or use as applicable rendered impossible; major unit is lost.	No portion of system can be salvaged; total loss.

5.11.1 *Promoted Ignition*—A source of heat input occurs (perhaps due to a kindling chain) that acts to start the metal burning. Examples: the ignition of contamination (oil or alien debris) which combusts and its own heat release starts a metal fire.

5.11.2 *Friction Ignition*—The rubbing of two solid materials results in the generation of heat and removal of protective oxide. Example: the rub of a centrifugal compressor rotor against its casing.

5.11.3 *Heat from Particle Impact*—Heat is generated from the transfer of kinetic, thermal, or chemical energy when small particles (sometimes incandescent, sometimes igniting on impact), moving at high velocity, strike a material. Example: high velocity particles from a dirty pipeline striking a valve plunger.

5.11.4 *Fresh Metal Exposure*—Heat is generated when a metal with a protective surface oxide is scratched or abraded, and a fresh surface oxide forms. Titanium has demonstrated ignition from this effect, but there are no known cases of similar ignition of other common metals. Nonetheless, fresh metal exposure may be a synergistic contributor to ignition by friction, particle impact, etc. Example: the breaking of a titanium wire in oxygen.

5.11.5 *Mechanical Impact*—Heat is generated from the transfer of kinetic energy when an object having a large mass or momentum strikes a material. Aluminum and titanium have been experimentally ignited this way, but stainless steels and carbon steels have not. Examples: a backhoe rooting-up an oxygen line; a fork truck penetrating an oxygen cylinder.

5.11.6 *Heat of Compression*—Heat is generated from the conversion of mechanical work when a gas is compressed from a low to a high pressure. This can occur when high-pressure oxygen is released into a dead-ended tube or pipe, quickly compressing the residual oxygen that was in the tube ahead of it. An effective ignition mechanism with polymers, the much higher heat capacity and thermal conductivity of significantly sized metals greatly attenuates high temperature produced this way. Example: a downstream valve or flexible lined pigtail in a dead-ended high-pressure oxygen manifold.

5.11.7 *Electrical Arc*—Electrical arcing can occur from motor brushes, electrical control instrumentation, other instrumentation, electrical power supplies, lightning, etc. Electrical arcing can be a very effective metal igniter, because current flow between metals is easily sustained, electron beam

heating occurs, and metal vaporizes under the influence of the plasma. All of these are conducive to combustion. Example: an insulated electric heater element in oxygen experiences a short circuit and arcs through to the oxygen gas.

5.11.8 *Resonance*—Acoustic oscillations within resonant cavities are associated with rapid gas temperature rise. This rise is more rapid and achieves higher values where particulates are present or where there are high gas velocities. Ignition can result if the heat transferred is not rapidly dissipated, and fires of aluminum have been induced experimentally by resonance. Example: a gas flow into a tee and out of a side port such that the remaining closed port forms a resonant chamber.

5.11.9 *Other*—Since little is known about the actual cause of some oxygen fires or explosions, other mechanisms, not readily apparent, may be factors in, or causes of, such incidents. These might include external sources, such as welding spatter, or internal sources, such as fracture or thermite reactions of iron oxide with aluminum.

5.12 *Reaction Effect*—The effect of an ignition (and subsequent propagation, if it should occur) has a strong bearing on the selection of a material. While reaction effect assessment is an obviously imprecise and strongly subjective judgment, it must be balanced against extenuating factors such as those given in 5.9. Suggested criteria for rating the reaction effect severity have been developed in Guide G 63 and are shown in Table 4, and a method of applying the rating in a material selection process is given in Section 8. Note that, in some cases, the reaction effect severity rating for a particular application can be lowered by changing other materials that may be present in the system, changing component locations, varying operating procedures, or using shields and the like (see Guide G 88).

5.12.1 *Heat of Combustion*—The combustion of a metal releases heat, and the quantity has a direct effect on the destructive nature of the fire. On a mass basis, numerous metals and polymers release about the same amount of heat. However, because of its much larger mass in most systems, combustion of many metals has the potential for release of the major amount of heat in a fire.

5.12.2 *Rate of Combustion*—The intensity of a fire is related to both the heat of combustion of the materials and the rate at which the combustion occurs. The rates of combustion of various metals can vary more than an order of

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magnitude, and for some metals can be so rapid as to be considered explosive.

6. Test Methods

6.1 Promoted Combustion Test—A metal specimen is deliberately exposed to the combustion of a promoter (easily ignited material) or other ignition source. The promoter may be standardized, in which case the test ranks those materials that resisted ignition as being superior to those that burned; varying the oxygen pressure or specimen temperature allows further ranking control. The promoter mass may also be varied, in which case, the metals are ranked according to the quantity of promoter required to bring about combustion. In yet another variation, ignition of the test specimen is ensured and the velocity of propagation or the specimen regression rate is measured. The regression rate is the velocity at which the combustion zone moves along the metal; the molten material that drains away may not be completely combusted. A low propagation rate ranks a metal higher (more desirable).

NOTE 5—ASTM Committee G-4 has sponsored a series of metal-promoted combustion tests at the NASA White Sands Test Facility using the methodology reported by Benz et al (13). These data, along with similar data generated by NASA, are included in Table XI.1. This table ranks metals according to (1) the highest pressure at which combustion was resisted, (2) for metals that ranked comparably above, according to the average propagation rate, and (3) for metals that ranked comparably by both (1) and (2), above, according to the average burn length below the threshold. The development of a standard for this test is underway by ASTM Committee G-4. (See Adjunct, Par 2.3).

6.2 Frictional Heating Test—One metal is rotated against another in an oxygen atmosphere. Test variables include oxygen pressure, specimen loads, and linear velocity. At constant test conditions, a material is ranked higher if it exhibits a higher Pv product at ignition (where P is the force divided by the initial cross-sectional area, and v is the linear velocity).

NOTE 6—ASTM Committee G-4 has sponsored a series of metals friction ignition tests at the NASA White Sands test facility using the methodology reported by Benz and Stoltzus (14). Due to the high cost of the apparatus and tests, round robin testing is not realistic and this procedure is not being developed into an ASTM standard; however, these data, along with similar data generated by NASA, are included in Table XI.2. (see adjunct par 2.3). Friction ignition is a very complex phenomenon. Test data suggest there is significance to the Pv product at the time of ignition (where P is the mechanical loading in force per apparent area, and v is the linear velocity), and this is the ranking criterion used in Table XI.2. Pressure affects friction ignition in that it has been harder to ignite metals at higher pressures above a minimum Pv value. In addition, in limited testing to date, the relative rankings of metals may change at different linear velocities.

6.3 Particle Impact Test—An oxidant stream with one or more entrained particles is impinged on a candidate metal target. The particles may be incandescent from preheating (likely for smaller particles) due to earlier impacts. The particles may be capable of ignition themselves upon impact (in this case, the test resembles a promoted ignition test under flowing conditions with the burning particle being the promoter). Test variables include pressure, particle and gas temperature, nature of particle, size and number of particles, and gas velocity.

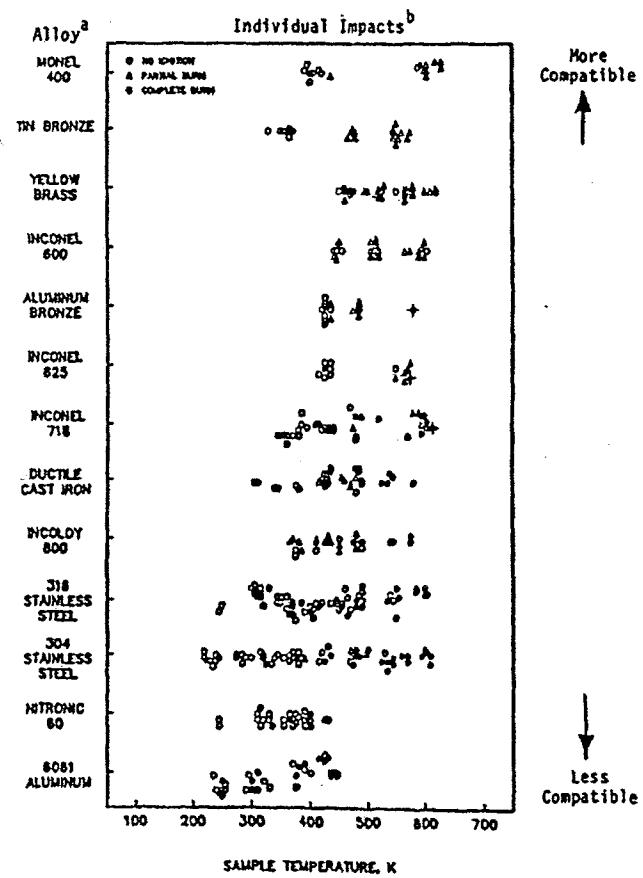
NOTE 7—ASTM Committee G-4 has sponsored a series of industry-funded particle impact tests at the NASA White Sands Test Facility using the methodology reported by Benz et al (15) in ASTM STP 910.

Due to high cost of the apparatus and test, round robin testing is not realistic, and this procedure is not being developed into an ASTM standard. Because of the scatter in these data, they are portrayed graphically and qualitatively ranked in Fig. 1. The results are qualitatively similar to those from the promoted combustion test (6.1), but with several significant exceptions. For example, aluminum bronze resisted particle impact ignition much better than aluminum; in the promoted combustion test, the results were more comparable.

6.4 Limiting Oxygen Index Test—This is a determination of the minimum concentration of oxygen in a flowing mixture of oxygen and a diluent that will just support propagation of combustion. There is a test method (see Test Method D 2863) that applies to nonmetals at atmospheric pressure, but a procedure for metals has not been standardized.

NOTE 8—The existence of an oxygen index for metals is established. The index of carbon steel decreases with increasing pressure. Data on the oxygen index of carbon steel have been reported by Benning and Werley (16), and the data are included in Table XI.3 and Fig. XI.1. The test is not currently undergoing standardization but is a candidate under study by ASTM Committee G-4.

6.5 Autoignition Temperature Test—A measurement of the minimum sample temperature at which a metal will spontaneously ignite when heated in an oxygen or oxygen-



NOTE—0.2 cm. (0.5 in.) diameter \times 0.24 cm. (0.60 in.) thick specimens impacted with 1600 μm , aluminum particles in 1000 psig oxygen, velocity \sim 1360 m/s.

^a See Table XI.8 for alloy compositions.

^b From Benz et al (15), Stoltzus (25).

NOTE—See adjunct, 2.3.

FIG. 1 Particle Impact Test Results

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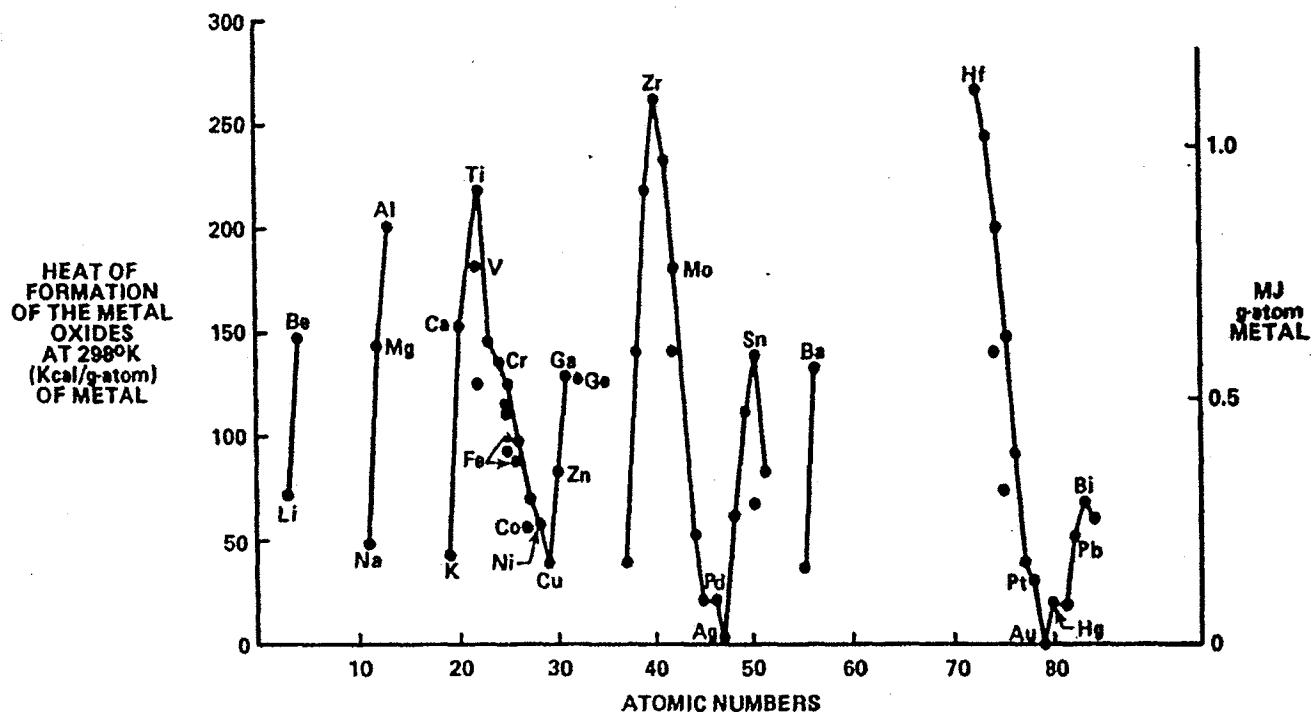


FIG. 2 Heat of Formation of the Metal Oxides versus Atomic Numbers

GROUP IA		METALS AVOIDED FOR HAZARDOUS OXYGEN SERVICE																		VIIA	
1	H	GOOD METALS FOR HAZARDOUS OXYGEN SERVICE																		2	He
3	Li																			10	Ne
11	Na																			18	Ar
19	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Al	Si	P	S	Cl	F	Ne		
37	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe			
55	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn			
87	Fr	Ra	Ac	104	58	59	60	61	62	63	64	65	66	67	68	69	70	71			
					Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			
					Curium	Protactinium	Neodymium	Promethium	Samarium	Europium	Dysprosium	Tytanum	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium			
					Thorium	Protactinium	Uranium	Neptunium	Plutonium	Anastassita	Cerium	Berkelium	Cf	Es	Fm	Md	No	Lw			

FIG. 3 Periodic Table Location of Some Hazardous Oxygen Service Metals

enriched atmosphere. Autoignition temperatures of nonmetals are commonly measured by methods such as Test Method G 72. Metals autoignite at much higher temperature than nonmetals (17, 18, 19). These temperatures are much higher than would occur in actual systems. Further, the experimental problems of containing the specimens, effects

of variable specimen sizes and shapes, effects of protective oxides that may be removed in actual systems, difficulty in measuring the temperature, and problems in deciding when ignition has occurred have prevented development of a reliable standard test procedure to yield meaningful data.

6.6 Mechanical Impact Test—A known mass is dropped

from a known height and impacts a test specimen immersed in oxidant. Two procedures, Test Methods D 2512 and G 86 have been used with nonmetals and are discussed in Guide G 63. Mechanical impact ignitions of metals are much less likely than for nonmetals; occasional ignitions have occurred during impact of zirconium, titanium, magnesium, and aluminum; however, ranking of other metals has not been achieved.

6.7 Calorimeter Test—A measurement of the heat evolved per unit mass (the heat of combustion) when a material is completely burned in 25 to 35 atm (2.5 to 3.5 MPa) of oxygen at constant volume. Several procedures such as Test Methods D 4809, D 2382 and D 2015 are used. The results are reported in calories per gram (or megajoules per kilogram). For many fire-resistant materials of interest to oxygen systems, measured amounts of combustion promoter must be added to ensure complete combustion.

NOTE 9—Heats of combustion for metallic elements and alloys have been reported by Lowrie (20) and are given in Table X1.4. In practice, it is usually not necessary to measure an alloy's heat of combustion, since it may be calculated from these data using the formula

$$\Delta H = \sum C_i \Delta H_i$$

where:

C_i = fractional weight concentration of the alloying element, and
 ΔH_i = heat of combustion of the alloying element (in consistent units). Heat of combustion per unit volume of metal can be calculated by the product of ΔH and density, ρ .

7. Pertinent Literature

7.1 Periodic Chart of the Elements—The periodic chart can provide insight into the oxygen compatibility of elemental metals. Grosse and Conway (1) and McKinley (21) have elaborated on this correlation. For example, Fig. 2 depicts the cyclic nature of heats of formation, and Fig. 3 shows the periodic chart with selected similar metals highlighted. Observe that the periodic chart shows how elements of demonstrated combustion resistance (such as the vertical columns Cu, Ag, Au, and Ni, Pd, Pt) are clustered together, as are elements of known flammability (such as Be, Mg, Ca, etc., and Ti, Zr, Hf, etc.).

7.2 Burn Ratios—A number of attempts have been made in the literature to relate the physicochemical properties of metals to their oxygen compatibility. Monroe et al. (22, 23) have proposed two "burn ratios" for understanding metals combustion: the melting-point burn ratio, BR_{mp} , and the boiling-point burn ratio, BR_{bp} . Although these factors lend insight into the burning of metallic elements, their application to alloys is complicated by imprecise melting and boiling points, vapor pressure enhancements and suppressions, potential preferential combustion of flammable constituents, and an importance of system heat losses that can alter the alloys rankings by these parameters.

7.2.1 Melting Point Burn Ratio—Numerous metals burn essentially in the molten state. Therefore, combustion of the metal must be able to produce melting of the metal itself. The BR_{mp} is a ratio of the heat released during combustion of a metal to the heat required to both warm the metal to its melting point and provide the latent heat of fusion. It is defined by:

$$BR_{mp} = \Delta H_{combustion}/(\Delta H_{n-mp} + \Delta H_{fusion})$$

where:

ΔH = heat of combustion,

ΔH_{n-mp} = heat required to warm the metal from room temperature, r_t , to the melting point, mp , and

ΔH_{fusion} = latent heat of fusion.

Clearly, a metal that does not contain sufficient heat to melt itself (that is, one that has a $BR_{mp} < 1$) is severely impeded from burning in the molten state. Monroe et al (22, 23) have calculated numerous BR_{mp} s and they are given in Table X1.5.

7.2.2 Boiling Point Burn Ratios—Several metals burn essentially in the vapor phase. Therefore, combustion of the metal must be able to produce vaporization of the metal itself. The BR_{bp} is a ratio of the heat released during combustion of a metal to the heat required to warm the metal to its boiling point and provide the latent heat of vaporization. It is defined by:

$$BR_{bp} = \Delta H_{combustion}/(\Delta H_{n-mp} + \Delta H_{fusion} + \Delta H_{mp-bp} + \Delta H_{vap})$$

where:

ΔH_{mp-bp} = heat required to warm the metal from the melting point to the boiling point, and

ΔH_{vap} = latent heat of vaporization.

Clearly, a metal that does not contain sufficient heat to vaporize itself (that is, one that has a $BR_{bp} < 1$) is severely impeded from vapor-phase combustion. Monroe et al. (22, 23) have calculated several BR_{bp} and they are given in Table X1.6. Since pure hydrocarbon materials burn in the vapor phase, a few BR_{bp} for hydrocarbons have been included in Table X1.6 for perspective.

7.3 Flame Temperature—The adiabatic flame temperature of a combusting material affects its ability to radiate heat. As a result, the adiabatic flame temperatures of metals give insight into the oxygen compatibility. Grosse and Conway (1) have tabulated the flame temperature for numerous metals and they are given in Table X1.7. These are compared to the flame temperatures of normal fuel gases reported by Lewis and Von Elbe (24). The adiabatic flame temperature is related to a material's heat of combustion. Other things being equal, a material of lower flame temperature is preferred.

8. Material Selection Method

8.1 Overview—To select a material for an application, the user first reviews the application to determine the probability that the chosen material will be exposed to significant ignition phenomena in service (8.2). The user then considers the prospective material's susceptibility to ignition (8.3) and its destructive potential or capacity to involve other materials (8.4) once ignited. Next, the potential effects of an ignition on the system environment are considered (8.5). Finally, the user compares the demands of the application with the level of performance anticipated from the material in the context of the necessity to avoid ignition and decides if the material will be acceptable (8.6). Examples of this regimen are given in 8.8.

8.2 Ignition Probability Assessment—In assessing a material's suitability for a specific oxygen application, the first step is to review the application for the presence of potential ignition mechanisms and the probability of their occurrence under both normal and reasonably foreseeable abnormal conditions. As shown in the Materials Evaluation Data Sheet, Fig. X1.2, values may be assigned, based on the following probability scale:

- 8.2.1 0—Almost impossible,
- 8.2.2 1—Remote,
- 8.2.3 2—Unlikely,
- 8.2.4 3—Probable, and
- 8.2.5 4—Highly probable.

8.2.6 This estimate is quite imprecise and generally subjective, but furnishes a basis for evaluating an application.

8.3 *Prospective Material Evaluation* — The next step is to determine the material's rating with respect to those factors which affect ease of ignition (5.8.1), assuming the material meets the other performance requirements of the application. If the required information is not available in the included tables (X1.1-X1.7) in published literature or from prior related experience, one or more of the applicable tests described in Section 6 should be conducted to obtain it. Typically, the most important criteria in the determination of a metal's susceptibility are dependent upon the application.

NOTE 10—Until an ASTM procedure is established for a particular test, test results are to be considered provisional.

8.4 *Post-Ignition Property Evaluation*—The properties and conditions that could affect potential resultant damage if ignition should occur (5.8.4) should be evaluated. Of particular importance is the total heat release potential, that is, the material's heat of combustion times its mass (in consistent units) and the rate at which that heat is released.

8.5 *Reaction Effect Assessment*—Based on the evaluation of 8.4, and the conditions of the complete system in which the material is to be used, the reaction effect should be assessed using Table 4 as a guide. In judging the severity level for entry on the Material Evaluation Data Sheet, Fig. X1.2, it is important to note that the severity level is defined by the most severe of any of the effects, that is, effect on personnel safety or on system objectives or on functional capability.

8.6 *Final Selection*—In the final analysis, the selection of a material for a particular application involves a complex interaction of the above steps, frequently with much subjective judgment, external influence, and compromise involved. While each case must ultimately be decided on its own merits, the following generalizations apply:

8.6.1 Use the least reactive material available consistent with sound engineering and economic practice. When all other things are equal, stress the properties most important to the application. Attempt to maximize frictional thresholds, promoted combustion thresholds, and oxygen index. Attempt to minimize heat of combustion, rate of propagation, flame temperature, burn ratios.

8.6.1.1 If the personnel injury or damage potential is high (code C or D) use the best (least reactive) practical material available (see Table 4).

8.6.1.2 If the personnel injury or damage potential is low (code A or B) and the ignition mechanism probability is low (2 or less), a material with medium reactivity may be used.

8.6.1.3 If one or more potential ignition mechanisms have a relatively high probability of occurrence (3 or 4 on the probability scale of 8.2), use only a material with a high resistance to ignition.

8.6.2 Metals of greater fire resistance should be chosen whenever a system contains large quantities of nonmetals, when less than optimum nonmetals are employed, or when sustained scrupulous cleanliness cannot be guaranteed.

8.6.3 The higher the maximum use pressure, the more critical is the metal's resistance to ignition and propagation (see 5.10.2).

8.6.4 Metals that did not propagate promoted combustion at or above 2500 psig (17.2 MPa) are preferred for demanding applications (see 6.1).

8.6.5 For rotating machinery, metals are preferred with the highest P_r values at ignition (see 6.2, Note 6) that are consistent with practical, functional capability.

8.6.6 Materials with high oxygen indices are preferable to materials with low oxygen indices. When a metal is used at concentrations below its pressure-dependent oxygen index, greater latitude may be exercised with other parameters (see 6.4).

NOTE 11—With respect to guidelines 8.6.4 through 8.6.6, the use of materials that yield intermediate test results is a matter of judgment involving consideration of all significant factors in the particular application.

8.6.7 Experience with a given metal in a similar or more severe application or a similar material in the same application, frequently forms a sound basis for a material selection. However, discretion should be used in the extrapolation of conditions. Similarities may be inferred from comparisons of test data, burn ratios, or use of the periodic chart of the elements.

8.6.8 Since flammability properties of metals can be very sensitive to small fractions of constituents, it may be necessary to test each alloy or even each batch, especially where very flammable elements are minor components.

8.7 *Documentation*—Figure X1.2 is a materials evaluation sheet filled out for a number of different applications. It indicates how a materials evaluation is made and what documentation is involved. Pertinent information such as operating conditions should be recorded; estimates of ignition mechanism probability and reaction effect ratings filled in; and a material selection made on the basis of the above guidelines. Explanatory remarks should be indicated by a letter in the "Remarks" column and noted following the table.

8.8 *Examples*—The following examples illustrate the metal selection procedure applied to three different hypothetical cases involving two centrifugal pumps and one case of a pipeline valve.

8.8.1 *Trailer Transfer Centrifugal Pump:*

8.8.1.1 *Application Description*—A pump is required to transfer liquid oxygen from tankers at 0 to 0.17 MPa (0 to 25 psig) to customer tanks at 0 to 1.7 MPa (0 to 250 psig). The pump will be remotely driven. Normal service vibration from over-the-road transport and frequent fill/empty cycles will make the introduction of contamination (hydrocarbon, lint, particles, etc.) a concern and may compromise pump reliability.

8.8.1.2 *Ignition Probability Assessment (See 8.2 and 5.11)*—Because of the demanding over-the-road use, frequent start-up, and potential contamination, the prospect of a rub, debris, or cavitation is significant. Hence, promoted ignition, particle impact and especially friction rubbing, are all rated likely.

8.8.1.3 Sources of heating are not present, nor is a mechanical impact. No other ignition sources are identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Promoted ignition	3
Friction	4
Particle impact	3
Temperature runaway	1
Mechanical impact	1
Other	1

8.8.1.4 *Prospective Material Evaluations (See 8.3)*—Pumps were found to be commercially available in stainless steels, aluminum, aluminum bronze and tin bronze. Among these, tin bronze ranks superior in tests of ignition by friction and promoted combustion; stainless steel and aluminum bronze rank lower; and aluminum ranks lowest (see Tables X1.1 and X1.2).

8.8.1.5 *Post-Ignition Property Evaluation (See 8.4)*—Both bronze and tin bronze have very low heats of combustion in the range 650 to 800 cal/g. Further, in promoted combustion tests (Table X1.1), tin bronze resisted propagation in 48 MPa (7000 psig) gaseous oxygen. Stainless steel propagated combustion in 7 MPa (1000 psig), but not 3.5 MPa (500 psig). Aluminum bronze propagated at its lowest test pressure of 3.5 MPa (500 psig). Aluminum propagated at its lowest test pressure of 1.7 MPa (250 psig).

8.8.1.6 *Reaction Effect Assessment (See 8.5)*—A rub or an ignition in the pump might expose the back of the tanker to fire and a potentially massive release of liquid oxygen. The tanker is equipped with tires and may have road tars and oils coating it. The driver is always present and might be injured, and the customer's facility could be damaged, as well. Hence, the following reaction effect assessment code ratings are assigned:

Effect on personnel safety	D
Effect on system objectives	C
Effect on function capability	C

Because of the importance of personnel safety, the overall rating is concluded to be a worst case D.

8.8.1.7 *Final Selection (See 8.6)*—In view of the overall catastrophic reaction assessment rating (Code D), only the most compatible available materials (bronze and tin bronze) are felt to be acceptable. An ignition event is likely to occur during the pump's life; however, Table X1.1 suggests bronze and tin bronze should be resistant to propagation. As a result, bronze was chosen on the basis of availability.

8.8.2 *Ground-Mounted Transfer Pump:*

8.8.2.1 *Application Description*—A pump is required to fill a high pressure liquid oxygen storage tank at gauge pressure of 0 to 1.7 MPa (0 to 250 psig) from a tanker at 175 kPa (25 psig). The pump will be remotely operated and will have a high duty cycle. It will be ground mounted with a filtered suction line, and a metal perimeter wall will shield it from other equipment. Remote valves will enable isolation of the liquid oxygen supplies in the event of a fire and shutdown devices protect it against cavitation. The area is isolated. Due to the high duty cycle, an efficient pump is desirable.

8.8.2.2 *Ignition Probability Assessment (See 8.2 and 5.1)*—Because of the rigid installation, semicontinuous operation, filtered suction, and permanent piping to its inlet, the worst operating problems are minimized. However, wear and mechanical failure can still operate to yield a frictional rub. Mechanical impact and a heat source are not foreseen. No other ignition sources are identified, but their absence cannot be assumed. The summary of ignition probability

ratings is:

Promoted ignition	2
Friction	3
Particle impact	2
Temperature runaway	1
Mechanical impact	1
Other	1

8.8.2.3 *Prospective Material Evaluation (See 8.3)*—Pumps were found to be commercially available in stainless steels, aluminum, aluminum bronze, tin bronze, and bronze. Among these, bronze and tin bronze ranked highest with stainless steel and aluminum bronze in a lower category, and aluminum ranks lowest (see Tables X1.1 and X1.2).

8.8.2.4 *Post-Ignition Property Evaluation (See 8.4)*—Both bronze and tin-bronze have low heats of combustion in the range from 650 to 800 cal/g. Both resisted propagation in 48 MPa (7000 psig) gaseous oxygen. Stainless steel alloys, specifically alloy 316 propagated in 7 MPa (1000 psig), but not 3.5 MPa (500 psig). Aluminum bronze propagated at its lowest test pressure of 3.5 MPa (500 psig). Aluminum ranked lowest and propagated at its lowest test pressure of 1.7 MPa (250 psig) with aluminum being the most energetic (heat of combustion of 7500 cal/g, see Table X1.4).

8.8.2.5 *Reaction Effect Assessment (See 8.5)*—A rub and ignition in the pump might release fire into the metal shield. Sustained liquid oxygen flow is unlikely because of shutoff devices outside the shield. Personnel do not approach the pump during operation, therefore risk of injury is minimal. Loss of the pump would be economically significant but the reliability of the overall arrangement render it an acceptable event. A spare pump is likely to be in inventory or on line. The plant mission would be interrupted for repairs, but replacement or repair can be obtained quickly, and, therefore, a fire would be a tolerable disruption. Hence, the following reaction effect assessment code ratings were assigned:

Effect on personnel safety	A
Effect on system objectives	B
Effect on function capability	B

The overall assessment is a marginal B rating.

8.8.2.6 *Final Selection (See 8.6)*—In view of the overall marginal reaction assessment rating (Code B), and, in particular, the safety of personnel, a wide latitude is acceptable in material selection. Since an event is possible due to mechanical failure, and since it can have the same impact (due to the failure itself) on system objectives and functional capability, and further since availability, operating economy and the like are important in this application, it was decided to choose any of the candidate metals that yielded the best reliability and efficiency, but if other things are equal, then to apply the ranking preference: bronze, tin bronze, stainless steels, aluminum bronze, aluminum. In order to have a rigid piping system, minimize flange loadings, and avoid flexible connections, a pump with a strong stainless steel case and a tin bronze impeller was chosen.

8.8.3 *Burner Isolation Valve:*

8.8.3.1 *Application Description*—A 50.8-mm (2-in.) carbon steel pipeline supplies gaseous oxygen to a burner from a 1.4-MPa (200-psig) liquid oxygen storage vessel. An isolation valve is required to allow periodic maintenance of the burners. The isolation valve is manually operated and requires a high capacity to satisfy flow requirements. The valve is operated infrequently to apply initial pressure to the system.

Gas velocities in the piping during normal operating conditions are limited to the values specified in CGA Pamphlet G-4.4.

8.8.3.2 Ignition Probability Assessment (See 8.2 and 5.11)—Due to a carbon steel system, some oxide particles are sure to be present and represent potential ignition sources at impact sites and for system polymers. Speed of valve operation is low in comparison to machinery, and friction ignition is, therefore, unlikely. Rapid opening of the valve can produce downstream adiabatic compression or turbulence that is undesirable in carbon steel piping. Heat inputs to the valve are not foreseen, and even rapid opening would not be expected to produce significant mechanical impact. Other ignition sources are not identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Promoted ignition	1
Friction	2
Particle impact	3
Temperature runaway	1
Mechanical impact	1
Other	1

8.8.3.3 Prospective Material Evaluations (See 8.3)—Valves of carbon steel, stainless steel, or brass are the most readily available and economical. Nickel/copper alloys (such as UNS N04400 Monel 400), and aluminum-bronze are less available alternatives at much greater cost. Regardless of material, heat of compression downstream of the valve and particle impingement are of concern. Using Table X1.1, these metals rank in decreasing compatibility in the order: nickel/copper and brass (similar), stainless steel, and aluminum bronze. Though carbon steel was not tested, a ranking below stainless steel would be anticipated.

8.8.3.4 Post Ignition Property Evaluation (See 8.4)—At the pressure of 1.4 MPa (200 psig), nickel/copper alloy and brass should resist combustion very effectively, having resisted propagation at 48 MPa (7000 psig) in the promoted combustion test. Stainless steel resisted propagation at 3.5 MPa (500 psig). Although these data (Table X1.1) do not prove that propagation will never occur in the valve, they are favorable in comparison to aluminum bronze's results in which propagation occurred at 3.5 MPa (500 psig), its lowest test pressure. Carbon steel is likely to propagate a substantial

fire at this pressure with extensive damage potential, and carbon steel is present in the downstream piping material.

8.8.3.5 Reaction Effect Assessment (See 8.5)—Since ignition is most likely during valve operation, and since the operation is manual, injury is likely. Ignition of the valve might yield ignition of the piping and significant propagation is likely regardless of valve material choice. A reaction of the valve would interrupt the plant operation; however, the repair would be relatively straightforward. Hence, the following reaction effect assessment code ratings are assigned:

Effect on personnel safety	D
Effect on system objectives	C
Effect on functional capability	B

The overall rating is D-catastrophic.

8.8.3.6 Final Selection (See 8.6)—In view of the overall catastrophic reaction assessment a highly fire-resistant alloy was felt to be required. Hence, brass or nickel/copper alloy were the choices. Welded connections to brass are a problem. Further, since turbulence downstream of the valve poses a concern, conversion from carbon steel piping to copper, brass or nickel/copper alloy was also felt necessary for at least 10 diameters downstream of the point of return to normal gas velocities (in keeping with CGA Pamphlet G-4.4). Even these steps, however, would not prevent rapid opening of the high-capacity valve, and a high-capacity valve itself would be difficult to obtain in a valve design that favored slow opening (in a plug valve as opposed to a ball valve). As a result, a different strategy was selected. A small bypass, globe valve of brass was piped around the main valve with copper tubing. Operating procedures were written to require that this fire-resistant bypass valve be used to do all pressurization slowly. Since the main valve is to be operated only under no-flow conditions, its risk of an ignition event is very low, and a carbon steel ball valve was selected.

9. Keywords

9.1 alloys; autoignition; autoignition temperature; burn ratios; calorimetry; combustion; flammability; friction/rubbing; gaseous impact; heat of combustion; ignition; LOX/GOX compatibility; materials selection; mechanical impact; metal combustion; metal flammability; metals; oxygen; oxygen index; oxygen service; particle impact; promoted combustion; sensitivity

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APPENDICES

(Nonmandatory Information)

X1. MATERIALS EVALUATION DATA SHEETS

X1.1 Introduction—The data sheet (Fig. X1.2) contains examples of typical applications divided into several functional categories such as valve components, piping, rotating machinery, etc. This data sheet will be revised periodically to include new applications and new suggested acceptance criteria, as more and better ASTM standard test procedures are developed. The following comments apply:

X1.1.1 The applications and the values shown are typical of those encountered in industrial and government agency practice and were chosen as examples of how this material evaluation procedure is used.

X1.1.2 The values shown in the various test columns are not necessarily actual test results, but, as indicated, are suggested minimum (or maximum for heat of combustion) test results required for acceptance. They are not to be construed as ASTM, industry, or government standards or specifications. Test data for selected materials are given in Tables X1.1, X1.2, X1.3, X1.4 and X1.5.

X1.1.3 In the "Examples of Materials in Use" column of the data sheet, various materials are indicated as being in current use for particular applications. This mention of particular materials is for information purposes only and

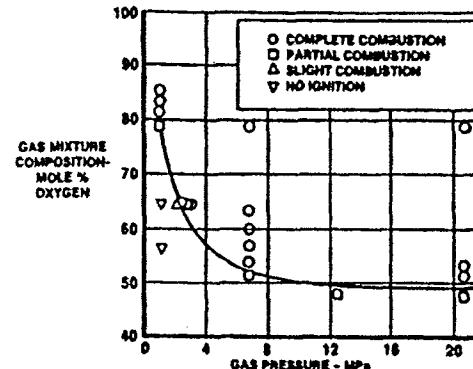


FIG. X1.1 Oxygen Index of Carbon Steel (Data from Table X1.3)

does not constitute an endorsement or recommendation by ASTM of a particular material. Furthermore, the omission of any material does not necessarily imply unsuitability.

X1.1.4 Unless otherwise noted, the operating conditions are for 99.5 mol %, or higher, oxygen.

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APPLICATION	OPERATING CONDITIONS		IGNITION MECHANISMS					REACTION EFFECT	SUGGESTED ACCEPTANCE CRITERIA								Examples of Materials in Use	Notes				
			Promoted Ignition	Friction Ignition	Particle Impact	Arc/Spark	Heat. Impact		Minimum Promoted Ignition Result	and	δ	Minimum Friction Test Result	and	δ	Minimum Particle Impact Result	and	δ	Maximum Heat of Combustion	and	δ	Other Methods	
	Tem- perature C	Gage Pressure psi	kPa						C	F		C	F		MJ/kg cal/g	20° F	60° F					

FIG. X1.2 Typical Material Evaluation Sheet

TABLE X1.1 Promoted Combustion Test Results
(0.23-g Aluminum Promoter)^a

Material ^b	Initial Pressure		Number of Tests	Average Propagation Rate		Average Burn Length		More Compatible
	MPa	(psig)		cm/s	(in./s)	cm	(in.)	
Copper 102	6.9	1000 ^c	2		NP ^d		...	...
	34.5	5000	2		NP		...	...
	55.1	8000	2		NP		...	...
Monel 400	3.5	500	1		NP		1.0	0.4
	6.9	1000 ^c	1		NP		...	...
	34.5	5000	2		NP		...	...
Nickel 200	55.1	8000	3		NP		...	...
	6.9	1000 ^c	1		NP		...	...
	34.5	5000	1		NP		...	...
Red Brass	55.1	8000	6		NP		...	...
	17.2	2500	1		NP		1.0	0.4
	34.5	5000	1		NP		1.5	0.6
Tin Bronze	48.3	7000	2		NP		0.6	0.2
	17.2	2500	1		NP		0.8	0.3
	34.5	5000	1		NP		0.8	0.3
Yellow Brass	48.3	7000	2		NP		0.3	0.1
	6.9	1000	1		NP		1.0	0.4
	17.2	2500	1		NP		1.0	0.4
	34.5	5000	1		NP		0.8	0.3
	48.3	7000	2		NP		0.5	0.2

NOTE—See Adjunct, par. 2.3.

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TABLE X1.1 Continued

Material ^B	Initial Pressure		Number of Tests	Average Propagation Rate		Average Burn Length	
	MPa	(psig)		cm/s	(in./s)	cm	(in.)
Inconel 600	6.9	1000	4	NP		0.5	0.2
	17.2	2500	3	NP		0.9	0.4
	17.2	2500	1	0.41	0.16	...	...
	24.8	3600	1 ^C	CB ^D		...	...
	34.5	5000	1	0.50	0.19	...	...
Stellite 6B	6.9	1000	4	NP ^D		0.7	0.3
	17.2	2500	2	NP		2.9	1.2
	17.2	2500	4 ^E	CB ^D		...	...
	17.2	2500	1	1.17	0.46	...	...
Inconel 625	34.5	5000	1	1.15	0.45	...	...
	6.9	1000	5	NP		2.2	0.9
	17.2	2500	1	0.99	0.39	...	...
Incoloy 800	17.2	2500	3 ^E	CB		...	...
	6.9	500	5	NP		1.1	0.4
	6.9	1000	1	NP		2.8	1.1
Inconel 718	6.9	1000	1	1.02	0.38	...	...
	17.2	2500	1	1.12	0.44	...	...
	17.2	2500	1 ^E	CB		...	...
	3.5	500	2	NPP ^D		0.5	0.2
	6.9	1000 ^C	4	1.12	0.44	...	...
304 Stainless Steel	6.9	1000	3	1.22	0.48	...	...
	27.6	4000	6	1.33	0.52	...	...
	48.2	7000	5	1.50	0.59	...	...
	68.9	10000	5	1.68	0.66	...	...
	3.5	500 ^C	10	NP		...	...
316 Stainless Steel	3.5	500	1	NP		2.3	0.9
	17.2	2500	1	1.12	0.44	...	...
	20.7	3000	10	1.19	0.47	...	...
	34.5	5000	1	1.30	0.51	...	...
	3.5	500 ^C	4	NP		...	...
Ductile Cast Iron	3.5	500	1	NP		3.3	1.3
	6.9	1000 ^C	5	1.12	0.44	...	...
	6.9	1000	1	1.02	0.40	...	...
	20.7	3000	2	1.22	0.48	...	...
	27.6	4000	6	1.24	0.49	...	...
	48.2	7000	5	1.44	0.57	...	...
	68.9	10000	4	1.58	0.62	...	...
	3.5	500	1	0.96	0.38	...	...
Nitronic 60	6.9	1000	1	0.69	0.27	...	...
	17.2	2500	8 ^E	CB ^D		...	...
	3.5	500	1	0.84	0.33	...	...
9 % Nickel Steel	6.9	1000	1	CB		...	...
	17.2	2500	6	CB		...	...
	3.5	500	1	0.96	0.38	...	...
	6.9	1000	1	1.35	0.53	...	...
Aluminum-Bronze	17.2	2500	1	1.70	0.67	...	...
	17.2	2500	1 ^E	CB		...	...
	3.5	500	1	2.77	1.09	...	...
	6.9	1000	1	2.79	1.10	...	...
	17.2	2500	1	3.30	1.30	...	...
Aluminum 6061	17.2	2500	3 ^E	CB		...	...
	34.5	5000	1	CB		...	...
	1.7	250	1	4.57	1.80	...	...
	3.5	500	1	5.84	2.30	...	...
	6.9	1000 ^C	4	6.42	2.53	...	...
	13.8	2000	2	8.85	3.48	...	...
	17.6	4000	7	13.86	5.46	...	...
C.	34.4	5000	2	14.82	5.83	...	...
	48.2	7000	2	18.93	7.45	...	...
	68.9	10000	3	24.51	9.65	...	...
							↓ Less Compatible

^A From Benz et al (13), Stoltzfus (25), specimens 3.2 mm (1/8 in) in diameter by 127 mm (5 in) long.^B See Table X1.8 for alloy compositions.^C A 3-L accumulator was added to the test chamber on all tests that were conducted at 3.5 or 6.9 MPa (500 or 1000 psig), except on those tests marked with footnote

C.

^D NP = Nonpropagating, CB = Completely burned.^E These tests were conducted using the video set-up. No burn rate was calculated.

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TABLE X1.2 Friction Ignition Test Data for Similar Pairs of Test Specimens

NOTE—2.5 cm (1 in.) diameter \times 0.25 cm (0.1 in. wall \times 2 cm (0.8 in.) specimens rotated axially, horizontally in stagnant 6.9 MPa (1000 psia), aviator's breathing grade oxygen. Tests were conducted by keeping v constant and increasing P at a rate of 35 N/s until ignition.
 P—specimen contact pressure at ignition (Loading force/initial contact area).
 v—specimen linear velocity is 11 m/s.

Test Materials ^a		Pv Product at Ignition
Stator	Rotor	W/m ² \times 10 ⁻⁶ (lb/in ² \times ft/min \times 10 ⁻⁶)
Inconel MA 754	Inconel MA 754	3.96-4.12 ^b 11.30-11.75
Haynes 214	Haynes 214	3.05-3.15 8.73-8.98
Inconel MA 758	Inconel MA 758	2.64-3.42 7.53-9.76
Nickel 200	Nickel 200	2.29-3.39 6.50-9.66 ^c
Tin Bronze	Tin Bronze	2.15-2.29 6.15-6.55 ^d
Hastelloy C-22	Hastelloy C-22	2.00-2.99 5.72-8.52
Inconel 600	Inconel 600	2.00-2.91 5.70-8.30 ^c
Inconel MA 6000	Inconel MA 6000	1.99-2.68 5.68-7.59
Gildcop Al-25	Gildcop Al-25	1.95-3.59 5.56-10.24
Hastelloy 230	Hastelloy 230	1.79-2.19 5.10-6.24
NASA-Z	NASA-Z	1.77-2.63 5.05-7.52
Cu Zr	Cu Zr	1.68-3.19 4.81-9.11
Inconel 625	Inconel 625	1.63-1.73 4.65-4.94
Hastelloy B-2	Hastelloy B-2	1.61-2.16 4.60-6.12
Waspaloy	Waspaloy	1.55-2.56 4.45-7.05
Monel 400	Monel 400	1.44-1.58 4.12-4.46 ^c
Haynes 230	Haynes 230	1.40-1.82 4.00-5.20
Monel K-500	Monel K-500	1.37-1.64 3.91-4.68 ^c
13-4 PH	13-4 PH	1.31-2.06 3.74-5.88 ^d
Hastelloy C-276	Hastelloy C-276	1.21-2.82 3.45-8.06
Incoloy 903	Incoloy 903	1.20-1.44 3.41-4.11
Inconel 718	Inconel 718	1.10-1.19 3.13-3.37
17-4 PH (H 900)	17-4 PH (H 900)	1.00-1.21 2.87-3.45
Yellow Brass	Yellow Brass	0.97-1.22 2.77-3.49
Hastelloy X	Hastelloy X	0.93-1.05 2.68-3.02 ^c
Hastelloy G30	Hastelloy G30	0.91-1.29 2.58-3.68
14-5 PH	14-5 PH	0.88-1.04 2.51-2.96
304 SS	304 SS	0.85-1.20 2.33-3.41
17-4 PH	17-4 PH	0.85-1.07 2.42-3.05
Inconel 706	Inconel 706	0.81-1.21 2.33-3.51
303 SS	303 SS	0.78-0.91 2.25-2.60
Stellite 6	Stellite 6	0.79-0.82 2.25-2.35
Brass CDA 360	Brass CDA 360	0.70-1.19 1.98-3.41 ^c
17-4 PH (Condition A)	17-4 PH (Condition A)	0.81-1.05 1.75-2.99
Invar 36	Invar 36	0.60-0.94 1.71-2.68 ^c
Incoloy MA 956	Incoloy MA 956	0.53-0.75 1.67-2.02
316 SS	316 SS	0.53-0.86 1.50-2.50 ^c
440 C Stainless Steel	440 C Stainless Steel	0.42-0.80 1.19-2.28
Nitronic 60	Nitronic 60	0.29-0.78 0.82-2.22
Incoloy 909	Incoloy 909	0.29-1.15 0.85-3.30
Aluminum 6061-T6	Aluminum 6061-T6	0.061 0.18 ^c
Ti-6Al-4V	Ti-6Al-4V	0.0035 0.01 ^c

^a Table X1.9 will be updated as required.

NOTE—All unreference data is from previously unpublished Frictional Heating Tests performed at NASA White Sands Test Facility.

^b This material did not ignite at these Pv products.^c From Benz & Stoltzus (14).^d From Stoltzus et al. (15).

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TABLE X1.3 Friction Ignition Test Data for Dissimilar Pairs of Test Specimens

NOTE—2.5 cm (1 in.) diameter \times 0.25 cm (0.1 in. wall \times 2 cm (0.8 in.) specimens rotated axially, horizontally in stagnant 6.9 MPa (1000 psia), aviator's breathing grade oxygen. Tests were conducted by keeping v constant and increasing P at a rate of 35 N/s until ignition.
 P —specimen contact pressure at ignition (Loading force/initial contact area).
 v —specimen linear velocity is 11 m/s.

Test Materials ^A		$W/m^2 \times 10^{-6}$	$(lb/in^2 \times ft/min \times 10^{-9})$
Stator	Rotor		
Monel K-500	Hastelloy C-22	1.57-3.72	4.51-10.61
Monel K-500	Hastelloy C-276	1.41-2.70	4.00-7.70
Monel K-500	Hastelloy G30	1.34-1.62	3.81-3.87
Ductile cast iron	Monel 400	1.28-1.45	3.65-4.13 ^B
Gray cast iron	410 SS	1.19-1.48	3.39-4.24 ^B
Gray cast iron	17-4 PH (H 1150 M)	1.17-1.66	3.35-4.75 ^B
Cu Be	Monel 400	1.10-1.20	3.14-3.42
Ductile cast iron	410 SS	1.10-1.23	3.12-3.43 ^B
AISI 4140	Monel K-500	1.09-1.35	3.10-3.85 ^B
Ductile cast iron	17-4 PH (H 1150 M)	1.09-1.17	3.00-3.35 ^B
Monel 400	Nitronic 60	1.03-1.69	2.93-4.78
Inconel 718	17-4 PH SS	1.02-1.12	2.91-3.20
Bronze	Monel K-500	0.99-1.84	2.82-5.26 ^B
Tin bronze	304 SS	0.97-1.25	2.78-3.56 ^B
Monel K-500	Inconel 625	0.93-2.00	2.67-5.70
17-4 PH SS	Hastelloy C-22	0.93-1.00	2.65-2.86
Monel K-500	304 SS	0.92-1.13	2.63-3.24
Inconel 718	304 SS	0.90-1.18	2.58-3.37
17-4 PH SS	Hastelloy C-276	0.89-1.10	2.55 3.14
Bronze	17-4 PH (H 1150 M)	0.89-1.02	2.55-2.90 ^B
316 SS	303 SS	0.89-0.90	2.53-2.57
Inconel 718	316 SS	0.86-0.96	2.44-2.73
Monel 400	304 SS	0.85-0.94	2.43-2.69
17-4 PH SS	Hastelloy G30	0.84-1.02	2.41-2.90
Monel K-500	303 SS	0.84-1.00	2.41-2.88
Ductile cast iron	Stellite 6	0.84-1.16	2.39-3.32 ^B
Cu Zr	316 SS	0.83-0.90	2.39-2.58
Ductile cast iron	Tin bronze	0.81-1.69	2.32-4.82 ^B
Monel K-500	17-4 PH SS	0.80-1.00	2.27-2.39
Bronze	410 SS	0.79-1.20	2.25-3.60 ^B
304 SS	303 SS	0.77-0.78	2.21-2.26
Tin bronze	Aluminum bronze	0.77-0.84	2.20-2.38 ^B
316 SS	17-4 PH SS	0.77-0.85	2.18-2.41
Monel 400	303 SS	0.76-0.93	2.17-2.67
304 SS	17-4 PH SS	0.75-1.09	2.14-3.12
Inconel 718	303 SS	0.75-0.86	2.14-2.48
Monel K-500	316 SS	0.73-0.91	2.10-2.61
316 SS	304 SS	0.68-0.91	1.93-2.60
Stellite 6	Nitronic 60	0.66-0.77	1.90-2.18 ^B
Monel 400	17-4 PH SS	0.66-1.53	1.89-4.38
303 SS	17-4 PH SS	0.65-0.88	1.86-2.51
17-4 PH SS	Inconel 625	0.64-1.09	1.83-3.11
304 SS	Cu Be	0.63-1.24	1.81-3.54
Monel 400	316 SS	0.62-0.91	1.75-2.59
Ductile Cast iron	Nitronic 60	0.44-0.75	1.25-2.15 ^B
Aluminum bronze	C355 Aluminum	0.30-0.32	0.85-0.91 ^B
Nitronic 60	17-4 PH (H 1150 M)	0.28-0.61	0.80-1.75 ^B
Babbitt on bronze	17-4 PH (H 1150 M)	0.09-0.21	0.25-0.60 ^B
Babbitt on bronze	Monel K-500	0.09-0.19	0.25-0.55 ^B
Babbitt on bronze	410 SS	0.08-0.09	0.24-0.27 ^B

NOTE—All unreferenced data is from previously unpublished Frictional Heating Tests performed at NASA White Sands Test Facility

^A Table X1.9 will be updated as required.

^B From Stoltzus et al. (15).

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TABLE X1.4 Oxygen Index of Carbon Steel^A

Gage Pressure		O ₂ Concentration, mol %	Result	Gage Pressure		O ₂ Concentration, mol %	Result
MPa	psi			MPa	psi		
1.03	150	56.7	N ^B	6.9	1000	50.7	S ^C
		56.8	N			51.0	P ^D
		64.5	N			51.0	P
		79.2	S			53.0	C ^E
		79.2	P			55.3	C
		80.9	C			56.8	P
		82.2	C			60.0	C
		84.2	C			63.0	C
2.1	300	65.0	S	12.4	1800	79.2	C
		65.0	S			48.5	P
2.4	350	65.0	S	20.7	3000	48.5	P
		65.0	C			51.0	C
						53.0	N
						53.1	C
2.8	400	64.6	P			79.2	C
		64.6	C				
3.1	450	64.6	C				

^A From Benning and Worley (16).^B N—no ignition.^C S—slight combustion.^D P—partial combustion.^E C—complete combustion C-1018 carbon steel specimens, 25 mm diameter × 4.8 mm wall, room temperature, 0.3 m/s downward gas velocity through specimen, upward propagation.

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TABLE X1.5 Heat of Combustion of Metals and Alloys

Material (Oxide Formed)	$-\Delta H_c$, cal/g ^A	$-\Delta H_c$, cal/cc ^B
Beryllium (BeO)	15 865	29 350
Aluminum (Al ₂ O ₃)	7 425	20 062
Magnesium (MgO)	5 900	10 266
Titanium (TiO ₂)	4 710	21 195
Chromium (Cr ₂ O ₃)	2 600	18 720
Ferritic and martensitic stainless steels	1 900-2 000	14 726-15 500
Austenitic stainless steels	1 850-1 900	14 850-15 251
Precipitation hardening stainless steels	1 850-1 950	14 390-15 167
Carbon steels	1 765-1 800	13 872-14 147
Iron (Fe ₂ O ₃)	1 765	13 872
Manganese	1 673 ^C	12 200
Molybdenum	1 458 ^C	14 900
Inconel 600	1 300	10 960
Aluminum bronzes	1 100-1 400	8 250-10 500
Zinc (ZnO)	1 270	9 068
Tin (SnO ₂)	1 170	7 628-8 517
Tungsten (WO ₃ , assumed)	1 093 ^D	21 094
Cobalt (CoO) ^E	970 ^E	8 633
Nickel (NiO)	980	8 722
Monel 400	870	7 682
Yellow brass, 60 Cu/40 Zn	825	6 914
Cartridge brass, 70 Cu/30 Zn	790	6 615
Red Brass, 85 Cu/15 Zn	690	5 966
Bronze, 10 Sn/2 Zn	655	5 751
Copper (CuO)	585	5 218
Cadmium (CdO)	541 ^D	4 679
Lead (PbO)	250	2 837
Palladium (PdO)	192 ^D	2 308
Platinum (PtO ₂)	164 ^{D, E}	3 520
Silver (Ag ₂ O)	35	368
Gold	1.9 ^C	37

^A 1 cal/g = 4.186 kJ/kg. Except as noted, from Lowrie (20).^B Calculated from $-\Delta H_c$ density. 1 cal/cc = 4.186 J/cc.^C From Hust and Clark (27).^D Heat of formation from Weast (26) and converted to cal/g.^E From Grosse and Conway (1).TABLE X1.6 Calculated Melting-Point Burn Ratios^A

Material	(BR) _{mp}
Silver	0.40
Copper	2.00
90:10 Copper-nickel ^B	2.39
CDA 938 Tin bronze ^B	2.83
CDA 314 Leaded commercial bronze ^B	2.57
Monel 400 ^B	3.02
Cobalt	3.50
Monel K 500 ^B	3.64
Nickel	3.70
CDA 828 Beryllium Copper ^B	4.49
AISI 4140 Low Alloy Steel ^B	5.10
Ductile iron	5.10
Cast Iron	5.10
AISI 1025 Carbon Steel ^B	5.10
Iron	5.10
17-4 PH ^B	5.32
410 SS ^B	5.39
CA 15 Stainless Steel ^B (See A 296)	5.39
304 Stainless Steel ^B	5.39
Titanium	13.1
Lead	18.8
Zinc	19.3
Lead Babbitt ^B	20.6
Magnesium	22.4
Aluminum	29.0
Tin Babbitt ^B	42.6
Tin	44.8

^A From Monroe et al (22, 23).^B Presented for comparison only. Alloys may exhibit flammability vastly inconsistent with the (BR)_{mp} ranking.TABLE X1.7 Calculated Boiling Point Burn Ratios^A

Material	(BR) _{bp}
Tin Babbitt ^B	0.78
Tin	0.8
Lead	0.9
Lead Babbitt ^B	1.0
Titanium	1.7
Aluminum	2.2
Zinc	2.4
Magnesium	3.6
Nonmetals ^C	
Ethylene Glycol	~17
Methyl Alcohol	~18
Acetone	~54
Toluene	~79
Ethyl Ether	~99

^A Metals data from Monroe et al (22, 23).^B Presented for comparison only. Alloys may exhibit flammability vastly inconsistent with the (BR)_{bp} ranking.^C Calculated.

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TABLE X1.8 Ranking of Metals and Selected Gases by Adiabatic Flame Temperature (1 atm Gaseous Oxygen)

Metals in 1 atm Gaseous Oxygen ^a	Temperature, K
Hf	4800
Zr	4800
Th	4700
Be	4300
Al	3800
Ca	3800
Sr	3500
Mn	3400
Mg	3350
Cr	3300
Tl	3300
Mo	3000
Fe	3000
Ba	3000
B	2900
Sn	2700
Li	2600
Zn	2200
Na	2000
Bi	2000
Pb	1800
K	1700
Ca	1700
Gases ^b	
21 % NH ₃ in air	1973
10 % CH ₄ in air	2148
9 % C ₂ H ₂ in air	2598
78 % H ₂ in O ₂	2933
70 % CO in O ₂	3198
44 % C ₂ H ₂ in O ₂	3410

^a From Grosse and Conway (1).^b From Lewis and Von Elbe (24).

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TABLE X1.9 Composition of Alloys

Metal/Alloy	UNS Number	Chemical Composition (by Weight Percent)																				
		Al	B	Be	C	Cr/Ta	Co	Cr	Cu	Fe	Mg	Mn	Ni	P	Pb	S	Sb	Si	Sn	Ti	W	Zn	Other
Tin Bronze	C90700	0.005	...	...	1.26	...	59.02	30.30	0.15	...	0.11	0.03	0.50	0.30	0.50 ^a	0.05	0.20	0.005	10-12	...	0.50	0.50
Stellite 68	R30006	...	...	0.75	...	16.60	0.42	60.85	...	8.33	0.21	8.27	0.37	...	0.0014	...	4.05	...	...	...	4.53	...
Nitronic 60	S21800	...	...	3.57	...	0.22	0.005	97.63	0.11	...	1.23	0.028	...	0.010	...	3.14	...	0.10	0.005	...	0.01	...
Ductile Cast Iron	F33100	...	1.84	...	...	...	...	...	61.79	0.10	...	0.04	...	0.003	...	...	0.10	0.005	...	...	35.01	...
Beryllium Copper	C17200	0.03	...	...	0.14	...	...	13.3	...	85.21	...	0.67	...	0.38	0.03	3.10	0.014	...	...	...	...	...
Yellow Brass	C36000	...	...	0.02	3.51	...	22.12	...	4.31	...	0.09	8.64	60.85	0.006	...	0.001	...	0.26	...	...	...	...
410 Stainless Steel	A41000	0.24	...	0.40	...	1.0	0.08	97.01	0.19	...	0.89	0.22	0.15	0.006	...	0.015	...	0.14	0.27	...	...	...
Inconel 625	N06625	...	0.06	0.18	...	...	...	30.79	1.78	...	1.02	...	65.92	...	0.003	...	0.24	...	...	...	...	...
AlSi 4140	G41400	...	...	...	...	...	...	91.12	...	...	...	...	...	...	...	...	1.8	...	...	...	...	...
Monel 400 (Cast)	N04400	0.06	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.0	0.12	0.02	0.02	...
Aluminum Bronze	C84200	7.0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.330	...	...	15.17	...
C 355 Aluminum	A03550	92.96	...	...	...	...	...	1.2	0.06	0.59	...	0.43	0.230	4.28	0.020	<0.001	0.024	...	...	...	0.45	...
17-4 PH (H 1150 M)	S17400	...	0.036	...	...	...	15.43	3.740	...	...	...	...	...	...	...	...	...	...	...	...	15.08	...
Red Brass	C23900	...	...	...	...	...	...	84.81	0.013	...	...	...	...	...	0.007	...	0.01	...	...	...	0.50	...
Incoloy 800	N08800	0.50	2.12	...	0.07	...	20.20	0.44	45.30	...	0.64	...	32.22	...	...	0.18	...	0.32	...	...	0.069	0.028
Colmonoy Alloy No. 70	N/A	...	...	0.66	...	0.04	11.43	...	3.71	...	...	...	65.76	...	...	0.14	...	0.14	...	...	0.50	...
Monel K-500 (Wrought)	N05500	2.92	...	0.16	...	...	30.29	0.60	...	0.70	...	64.69	...	...	0.001	...	0.24	...	...	...	...	...
9 % Nickel Steel	K81340	...	0.06	...	0.04	...	...	90.026	...	0.61	...	9.06	0.003	...	0.001	...	0.60	...	...	...	...	...
6061 Aluminum	A96061	97.643	...	0.04	...	0.13	0.17	0.41	0.91	...	...	...	...	...	...	...	...	...	...	...	...	...
304 Stainless Steel	S30403	...	...	0.021	...	0.08	18.50	0.38	69.206	...	1.44	0.24	9.36	0.027	...	0.026	...	0.70	0.02	...	...	...
Gray Cast Iron	F10006	...	...	3.32	...	...	...	...	83.763	...	0.90	...	74.63	...	...	0.097	...	1.90	...	...	...	...
Inconel 600	N06600	...	0.07	...	...	15.05	0.36	9.42	...	0.38	...	...	...	...	0.004	...	0.09	...	...	...	...	...
SAE 11 Babbitt	N/A	...	...	...	...	...	...	5.7	...	...	...	...	...	0.17	...	0.17	...	...	...	...	...	...
Bronze	C93800	0.005	...	...	...	...	...	75.79	0.15	...	...	...	1.0	0.5	13-16	0.08	0.80	0.005	7.5	...	0.8	...
14-6 PH Stainless Steel	S45000	...	0.024	...	14.03	1.44	76.768	...	0.44	1.32	5.35	0.016	...	0.002	...	0.29	...	0.50	0.50	...	0.30	...
13-4 Stainless Steel	J81540	...	0.082	...	12.23	...	82.579	...	0.65	0.45	3.50	0.018	...	0.011	...	...	...	...	...	...	...	...

^a Maximum

X2. ADDITIONAL LITERATURE

X2.1 Introduction—The following are abstracts of a representative selection of articles and reports on testing and application of metals in oxygen environments. They are illustrative of the types of testing and evaluation that have been conducted on a variety of metals.

X2.2 Promoted Combustion:

X2.2.1 Compatibility of Materials With 7500 psi Oxygen (28)—A research program was conducted to develop ignition data on thread lubricants, thread sealants, fluorocarbon plastics, and metals. The relative ease of ignition of metals and alloys was determined by promoted ignition methods in oxygen at 7500 psi (52 MPa). Inconel alloy 600, brass, Monel alloy 400, and nickel were found to have the highest resistance to ignition and combustion among the common alloys and metals. Of the metals tested, stainless steel and aluminum are the least satisfactory for use at oxygen pressures of 7500 psig (52 MPa). Although the test results for aluminum are better than those for copper, the authors rank aluminum least satisfactory "because of its violent reaction once it becomes ignited." The test involved heating a specimen of 0.005 in. metal foil and a variable quantity of neoprene promoter to the promoter's ignition temperature, and ranking the metals by the quantity of promoter required to completely combust the metal. Ten metals that were ranked at 7500 psi (52 MPa) are given in Table X2.1.

X2.2.2 Selection of Metals for Gaseous Oxygen Service (29)—Selection of metals for gaseous oxygen service requires consideration of compatibility test data and the design of the specific component. Of the various oxygen compatibility tests, the promoted ignition test provides one measure of the performance of a metal in gaseous oxygen. Promoted ignition test results for copper alloys, nickel alloys, and iron alloys are reviewed. The use of the extended fire triangle to predict the performance of a component is discussed. Materials are selected for a hypothetical control valve for 1.7 MPa (250 psi) oxygen service by considering compatibility test data and valve design. The authors rank four metals in terms of the percentage loss after ignition in 1.7 MPa oxygen flowing through the specimen:

% Loss

Monel	1.1
304 stainless steel	3.4 and 3.5
Gray cast iron	5.1 and 8.3
Carbon steel	100 and 100

X2.2.3 Studies on Combustibility and Ignitability of Metal Tubing in Stationary and Flowing Oxygen (30)—Tubes of 4

TABLE X2.1 Compatibility of Materials with 7500 psi Oxygen

	Required Promoter
Gold	only melts
Silver	only melts
Nickel	48–56 mg (est.)
Monel 400	18–19 mg (est.)
Yellow brass (partial combustion only)	11.8–15.2 mg
Inconel 600	13.2 mg
Aluminum	11.0–16.4 mg
Copper	10.5 mg (est.)
Inconel X-750	9.0 mg
Stainless steel	7.1–8.5 mg

mm inside diameter × 3.0 mm wall × 500 mm long of fourteen different metals were tested by igniting the inner walls using fuse-wire-ignited Perburan of mass 3.4 g enclosed in 0.5 mm thick I ST V 23 (steel) sheet of mass 12 g. Oxygen pressure of 16 atm was used. Extensive discussion is included on theory and practice of metal use. An overall order of merit for the metals is given in Table X2.2.

X2.2.4 Promoted Ignition Behavior of Engineering Alloys in High Pressure Oxygen (31)—Promoted ignition involves a scenario in which a substance with low compatibility with oxygen ignited and promotes the ignition of a more oxygen compatible material. For example, in oxygen systems hydrocarbon contaminants could result in the promoted ignition of a structural alloy. An investigation of the promoted ignition behavior of several engineering alloys was made in oxygen at pressure up to 38.6 MPa (5600 psig) see Table X2.3. Aluminum, carbon steel, cuprous, nickel, and stainless steel alloys were investigated. The effects of different promoters were observed. Alloy composition, oxygen pressure, and promoter type were found to be significant variables in the promoted ignition tests. The following table reports the measured upwards burn rates of 8 alloys for 1/8-in. diameter rod samples. Aluminum has the highest rate and is surprisingly followed by aluminum bronze. Inconel 718, Incoloy 825, stainless steel and carbon steel burn at a nominal rate of 1 cm/s.

TABLE X2.2 Combustibility and Ignitability of Metal Tubing in Stationary and Flowing Oxygen

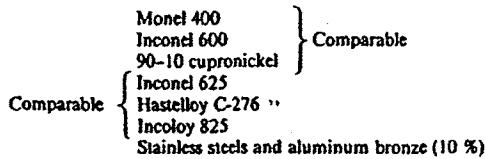
Copper	D-CuF 25	more compatible ↑
Ferritic chromium steel	G-X 40 Cr Si 22	
Austenitic chromium steel	X 5 Cr Ni 189	
Brass	So Ms 58 Al 2	
Brass	G-So Ms 57 F 45	
Nickel-aluminum bronze	G-Ni Al Bz F 60	
Tin bronze	G-Sn Bz 10	
Gun metal	Rg 10	
Flake graphite iron	GG26	
Spheroidal graphite iron	GGG38	
Aluminum	Al 99	
Aluminum	Al Mg 5	
Steel	30 Cr Mo V 9	↓ less compatible
Steel	St 35	

TABLE X2.3 Burn Rates of Various Alloys in High Pressure Oxygen

Alloy	Test Pressure MPa	Burn Rate cm/s
Carbon steel	20.8	3020
Carbon steel	10.8	1584
430 stainless steel	34.1	4950
430 stainless steel	8.3	1200
304 stainless steel	35.2	5100
304 stainless steel	20.8	3020
304 stainless steel	7.6	1100
316 stainless steel	35.1	5090
316 stainless steel	21.7	3150
Aluminum bronze, 11% Al	35.3	5120
Aluminum bronze, 7% Al	38.3	5550
Inconel 718	35.5	5150
Incoloy 825	35.9	5200
1100 aluminum ^A	7.6	1100

^A Aluminum alloy 1100 exhibited the highest burn rate of the alloys tested even though the maximum test pressure was only 20% of the highest oxygen pressures tested.

X2.2.5 Material Compatibility and Systems Considerations in Thermal EOR Environments Containing High Pressure (32)—This paper considers the application of carbon steel and other alloys in hostile corrosion environments and high pressure gaseous oxygen. Testing of $\frac{1}{4}$ -in. diameter metal samples in the promoted metals ignition tester using oil as the promoter showed that carbon steel is consumed at pressures of 700 psi and higher. Other alloys showed no ignition at 5000 psi oxygen: these included 304SS, Monel 400, Inconel 600 and 625, Hastelloy C-276, Incoloy 825, 90/10 Cupronickel, and aluminum bronze. With an oil plus iron wire promoter, testing allows the ranking of the alloys in the following manner:



For carbon steel, Fig. X2.1 is shown comparing sample upwards burn rate at 1500 and 3000 psig, gas pressure with oxygen concentration above 50 %.

X2.3 Frictional Heating:

X2.3.1 Friction-Induced Ignition in Oxygen (33)—The friction-induced ignition of structural materials in oxygen has been investigated. A test arrangement has been designed that allows basic data for the oxidation reaction rate to be determined for various materials or pairs of materials. The rate at which oxidation energy is released at the rubbing interface is obtained from the difference in measured friction power necessary to produce the same interface temperatures in tests with oxygen and an inert gas. These results are then correlated by the Arrhenius rate law, allowing the oxidation reaction rate factors for the different materials to be determined.

X2.3.2 The theoretical simulation of the ignition process for the test arrangement using these data is in good agreement with the observed experimental results. This suggests

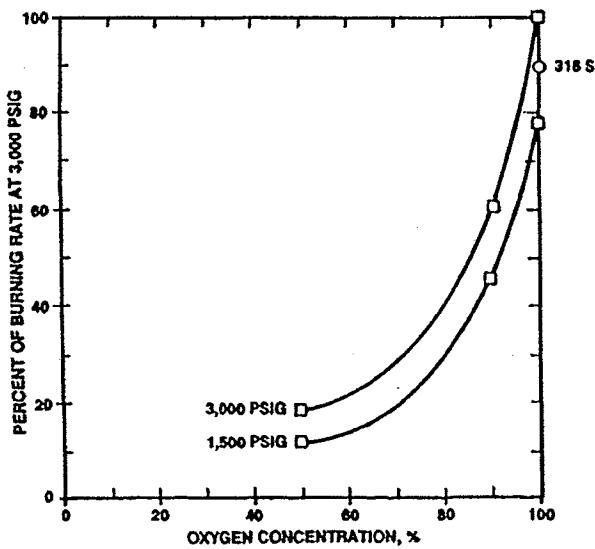


FIG. X2.1 Carbon Steel Burning Rate versus Oxygen Concentration

that the geometry, ambient temperature, and gas velocity, that have a primary effect on heat dissipation are adequately taken into account by the theoretical model.

X2.3.3 In addition to the collection of these basic data, the test allows materials to be classified for oxygen compatibility under friction simply by means of comparing the axial load necessary for ignition. Of the pairs of materials tested, Monel was found to give the highest ranking, followed by stainless steel/cast iron and bronze. The propagation of combustion after ignition was smallest with Monel, followed by bronze, and was largest for stainless steel/cast iron.

X2.4 Particle Impact:

X2.4.1 Investigations on the Safe Flow Velocity to be Admitted for Oxygen in Steel Pipe Lines (34)—Risks of fire due to solid contamination in steel oxygen pipelines was investigated. The velocity of oxygen through an ST40 nominal width 40 trial section of pipe was varied to try and cause ignition. The trial section was either straight, or contained a sequence of four right-angle elbows. Pressures were in the range 27 to 29 atm, and the gas stream entrained 1 to 2 kg of solid materials in the form of sand, rust, flue dust, mill cinder, welding cinder, coke, steinkohl (a bituminous coal), or a mixture of 20 % iron powder and 80 % sand.

X2.4.2 The noncombustible solids of rust, fluedust, and sand did not produce steel fires nor were glowing particles observed at the outlet. Mill cinder produced glowing particles at 28 m/s and pipe ignition at 52 m/s. Welding cinder produced glowing particles at the vent at 44 m/s in the straight pipe and at 17 m/s in the circuitous pipe, but pipe fires did not occur even at 53 m/s. Coke, steinkohl, and iron powder produced pipe fires. Glowing particles of coke emerged from the straight pipe at 30 m/s, from the circuitous pipe at 17 m/s, and a pipe fire occurred at 53 m/s. Stone coal ignited in the straight and circuitous pipe at 13 m/s, and pipe fire resulted at 34 m/s. The iron powder mixture exhibited sparks at 13 m/s, and pipe fires resulted at 28 m/s. Most pipe fires occurred immediately downstream of elbows.

X2.5 Mechanical Impact:

X2.5.1 Fire Tests on Centrifugal Pumps for Liquid Oxygen (35)—As part of a project to test liquid oxygen pumps, drop hammer (mechanical impact) tests of several metals tested as 1 to 2 g of loose metal chips or chips pressed into pills are reported. The drop weight was 25 kg (245 N) at drop heights up to 3 m. The results are given in Table X2.4.

TABLE X2.4 Impact Tests on Liquid Oxygen Pumps^A

	Impact energy, J	
	No Reaction	Reaction
Anticorodal 70 (92 Al, 7 Si, 0.4 Mg, 0.12 Ti)	190	250 (pill)
	60	130 (chips)
Silmon 5 (89 Al, 9.5 Si, 0.5 Co, 0.5 Fe, 0.3 Mg)	380	500 (pill)
	380	500 (chips)
Solder (45 tin, 55 lead)	250	380 (pill)
	60	130 (chips)

^A The authors note the following metals failed to react to impact energies up to the maximum available of 735 J: stainless steel (4300) X12 CrNi 8.8 [18.0 Cr, 8.5 Ni]; stainless steel (4312) GX 15 CrNi 18.8 [18.0 Cr, 8 Ni]; nickel steel (5662) X8 Ni9 [8.0–10.0 Ni]; bronze GBz14 [86 Cu, 14 Sn, 1.0 Pb]; copper; and hard solder (40 % Ag).

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EXHIBIT 65

ORIGINAL

UNITED STATES DISTRICT COURT
DISTRICT OF DELAWARE

*
NORTHEAST CONTROLS, INC. and)
ST. PAUL MERCURY INSURANCE)
COMPANY,)
Plaintiffs,)
)
- against-) CA# CV-06-412
)
FISHER CONTROLS)
INTERNATIONAL, LLC,)
Defendant.)
*)

DEPOSITION OF NORTHEAST CONTROLS, INC., a Plaintiff, by and through their representative, ALBERT CAPPELLINI, conducted pursuant to Notice at the law offices of THORN, GERSHON, TYMANN & BONANNI, 5 Wembley Court, Albany, New York, on October 24, 2007, commencing at approximately 9:30 a.m. before Lynne Billington, a Shorthand Reporter and Notary Public in and for the State of New York.

A P P E A R A N C E S:

FOR THE PLAINTIFFS:

MARSHALL, DENNEHEY, WARNER, COLEMAN & GOGGIN
1845 Walnut Street
Philadelphia, PA 19103
By: Thomas P. Wagner, Esq.

FOR THE DEFENDANT:

RIDDELL WILLIAMS
1001 Fourth Avenue Plaza, Suite 4500
Seattle, WA 98154
By: Daniel J. Gunter, Esq.

ALSO PRESENT:

Meredith Miller (via phone)

FCI/MSJ 0819

1 ALBERT CAPPELLINI,
2 was called as a witness by the Defendant and, having
3 been first duly sworn, testified as follows:

4
5 EXAMINATION
6

7 BY MR. GUNTER:
8

9 Q Mr. Cappellini, could you state your full
10 name and spell your last name for the record, please?

11 A Albert Cappellini, C-a-p-p-e-l-l-i-n-i.

12 Q And what is your residence address,
13 Mr. Cappellini?

14 A 868 Edgewater Drive, Amherst, New York 14228.

15 Q Are you currently employed?

16 A Yes.

17 Q And by whom are you employed?

18 A Northeast Controls.

19 MR. WAGNER: I'm sorry, Counsel, to
20 interrupt.

21 Stipulations?

22 MR. GUNTER: Same as we had yesterday.

23 MR. WAGNER: Same as we had in the other

1 contact with the flow stream be made of copper, copper
2 alloy, or nickel-copper alloys, correct?

3 A Correct.

4 Q And you wouldn't have had in the summer of
5 1998 any reason to disagree with Fisher in regard to
6 that recommendation, would you?

7 A Not using this? I would go on the customer
8 recommendation.

9 Q Okay.

10 You wouldn't have had independently decided
11 what materials to use in the oxygen flow stream for a
12 valve in oxygen service, right?

13 A Independently, no.

14 Q Okay.

15 You would have relied on the customer to
16 provide you that information, correct?

17 A Correct.

18 Q And you understood in the summer of 1998 that
19 Praxair was involved in the industrial gases industry,
20 correct?

21 A Yes.

22 Q You understood that within that industry one
23 of the things they do is provide oxygen service,

1 C E R T I F I C A T E
2

3 I, Lynne Billington, a Shorthand Reporter and
4 Notary Public in and for the State of New York, do
5 hereby certify that the foregoing is a true, correct
6 and complete transcript of the testimony of ALBERT
7 CAPPELLINI taken on October 24, 2007 in the proceedings
8 as mentioned in the heading hereof, to the best of my
9 knowledge, and belief

10 IN WITNESS THEREOF I hereby set my hand
11 this 30th day of October, 2007.

12
13
14 
15 LYNNE BILLINGTON, Notary Public

16 My commission expires:
17 December 14, 2010
18
19
20
21
22

23

FCI/MSJ 0822

EXHIBIT 66

ORIGINAL

UNITED STATES DISTRICT COURT
DISTRICT OF DELAWARE

* * * * *

NORTHEAST CONTROLS, INC. and)
ST. PAUL MERCURY INSURANCE)
COMPANY,)
Plaintiffs,)
)
- against-) CA# CV-06-412
)
FISHER CONTROLS)
INTERNATIONAL, LLC,)
Defendant.)
)

* * * * *

DEPOSITION OF NORTHEAST CONTROLS, INC., a Plaintiff, by and through their representative, MICHAEL J. PETERS, conducted pursuant to Notice at the law offices of THORN, GERSHON, TYMANN & BONANNI, 5 Wembley Court, Albany, New York, on October 22, 2007, commencing at approximately 9:30 a.m. before Lynne Billington, a Shorthand Reporter and Notary Public in and for the State of New York.

A P P E A R A N C E S:

FOR THE PLAINTIFFS:

MARSHALL, DENNEHEY, WARNER, COLEMAN & GOGGIN
1845 Walnut Street
Philadelphia, PA 19103
By: Thomas P. Wagner, Esq.

FOR THE DEFENDANT:

RIDDELL WILLIAMS
1001 Fourth Avenue Plaza, Suite 4500
Seattle, WA 98154
By: Daniel J. Gunter, Esq.

ALSO PRESENT:

Mary Elizabeth Slevin, Esq.
Meredith Miller (via phone)

FCI/MSJ 0823

1 MICHAEL J. PETERS,
2 was called as a witness by the Defendant and, having
3 been first duly sworn, testified as follows:
4

5 EXAMINATION
6

7 BY MR. GUNTER:

8
9 Q Mr. Peters, could you state your full name
10 and spell your last name for the record?

11 A Michael John Peters. P-e-t-e-r-s.

12 Q And what is your residence, Mr. Peters?

13 A My residence?

14 Q Yeah.

15 A Meaning the address?

16 Q Your residence address.

17 A Where I live?

18 Q Yes.

19 A 51 Timberwick Drive, Clifton Park.

20 Q New York?

21 A New York.

FCI/MSJ 0824

22 MR. WAGNER: Mr. Gunter, before we go
23 further, stipulations. Same as we had for Mr. Bhakoo?

1 A It is. It is.

2 Q Okay.

3 There are oral discussions between the sales
4 representative and a customer as to specifications for
5 a product. It's also good general business practice to
6 confirm those specifications in writing, isn't it?

7 A It is.

8 Q And if Praxair and Northeast Controls agreed
9 on a set of specifications for a Fisher product,
10 Northeast Controls would not have made a practice to
11 substitute different specifications to Fisher without
12 first obtaining Praxair's agreement, right?

13 A Correct.

14 Q In 1998, Northeast Controls understood that
15 Praxair was in the industrial gases industry, correct?

16 A Absolutely.

17 Q You understood that part of Praxair's work
18 was specifically in the oxygen service industry,
19 correct?

20 A Yes.

21 Q And Northeast Controls did not hold itself
22 out as being an expert in oxygen service, correct?

23 A Correct.

FCI/MSJ 0825

1 Q Northeast Controls did know, though, that
2 there are hazards associated with oxygen service,
3 correct?

4 A Yes.

5 MR. GUNTER: This is Deposition
6 Exhibit 35.

7
8 (NEC Exhibit Number 35 was marked for
9 identification.)

10
11 Q (By Mr. Gunter) Mr. Peters, handing you
12 what's been marked as Deposition Exhibit 35, I'd ask
13 you to review that briefly.

14 A (Witness complies.)

15 Finished.

16 Q Okay.

17 Having reviewed Deposition Exhibit 35,
18 Mr. Peters, have you previously seen that document?

19 A I believe I have, yeah.

20 Q Okay.

21 And this document is headed Material
22 Guidelines for Gaseous Oxygen Service, correct?

23 A Yes.

FCI/MSJ 0826

1 C E R T I F I C A T E
2

3 I, Lynne Billington, a Shorthand Reporter and
4 Notary Public in and for the State of New York, do
5 hereby certify that the foregoing is a true, correct
6 and complete transcript of the testimony of MICHEAL J.
7 PETERS taken on October 23, 2007 in the proceedings as
8 mentioned in the heading hereof, to the best of my
9 knowledge, and belief

10 IN WITNESS THEREOF I hereby set my hand
11 this 30th day of October, 2007.

12
13
14 
15 LYNNE BILLINGTON, Notary Public

16 My commission expires:
17 December 14, 2010
18
19
20
21
22

23 FCI/MSJ 0827

EXHIBIT 67

IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

NORTHEAST CONTROLS, INC.,)
ST. PAUL MERCURY)
INSURANCE COMPANY,)
)
Plaintiffs,)
) Civil Action
v.) No. 06-412
)
FISHER CONTROLS)
INTERNATIONAL, LLC,)
)
Defendant.)

Deposition of DAVID P. POPE, Ph.D. taken pursuant to notice at the law offices of Maron, Marvel, Bradley & Anderson, P.A., 1700 Market Street, Suite 1500, Philadelphia, Pennsylvania, beginning at 9:45 a.m., on Wednesday, October 17, 2007, before Kurt A. Fetzer, Registered Diplomatic Reporter and Notary Public.

APPEARANCES:

THOMAS P. WAGNER, ESQ.
MARSHALL DENNEHEY WARNER COLEMAN & GOGGIN
1845 Walnut Street
Philadelphia, Pennsylvania 19103
For the Plaintiffs

DANIEL J. GUNTER, ESQ.
RIDDELL WILLIAMS P.S.
1001 Fourth Avenue Plaza - Suite 4500
Seattle, Washington 98154-1065
For the Defendant

WILCOX & FETZER
1330 King Street - Wilmington, Delaware 19801
(302) 655-0477
www.wilfet.com



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1 power plant incident also identifies burning of the
2 Hastelloy C disk and the Inconel 718 shaft. Is that
3 correct?

4 A. Like I said, I didn't read that report, but I
5 would not disagree with that statement.

6 Q. You understand that that report was published
7 in a peer-reviewed journal?

8 A. The ASTM journal, that's the one you're
9 referring to?

10 Q. Yes.

11 A. Yes. That's a peer-reviewed journal, yes.

12 Q. Would you rely typically on articles from that
13 journal in forming opinions?

14 A. I commonly would, yes.

15 Q. Do you consider that journal to be
16 authoritative?

17 A. Yes.

18 Q. I would like to turn your attention back to,
19 having taken that detour, to Exhibit 29. I would like
20 to turn your attention -- well, let's start with the
21 first page.

22 We see at the top of this page the authors
23 of this article and the first author is Robert
24 Zawierucha, correct?



1 State of Delaware)
2)
2 New Castle County)
3

4 CERTIFICATE OF REPORTER

5 I, Kurt A. Fetzer, Registered Diplomate
6 Reporter and Notary Public, do hereby certify that
7 there came before me on Wednesday, October 17, 2007,
8 the deponent herein, DAVID P. POPE, Ph.D., who was
9 duly sworn by me and thereafter examined by counsel
10 for the respective parties; that the questions asked
of said deponent and the answers given were taken down
by me in Stenotype notes and thereafter transcribed by
use of computer-aided transcription and computer
printer under my direction.

11 I further certify that the foregoing is a true
12 and correct transcript of the testimony given at said
examination of said witness.

13 I further certify that I am not counsel,
14 attorney, or relative of either party, or otherwise
interested in the event of this suit.

15

16

17 Kurt A. Fetzer, RDR, CRR
18 Certification No. 100-RPR
19 (Expires January 31, 2008)

20 DATED:



21

22

23

24

W&F

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EXHIBIT 68

IN THE SUPERIOR COURT OF THE STATE OF DELAWARE

IN AND FOR NEW CASTLE COUNTY

RONALD W. OLSON, and CAROL) CONFIDENTIAL
OLSON, his wife,)
)
 Plaintiffs,)
) Civil Action No.
 v.) 02C-04-263 (JRS)
)
 MOTIVA ENTERPRISES L.L.C.;)
 BATTAGLIA MECHANICAL, INC.;)
 FISHER CONTROLS INTERNATIONAL,)
 INC.; HYDROCHEM INDUSTRIAL)
 SERVICES, INC.; JJ WHITE, INC.;)
 NORTHEAST CONTROLS, INC.;)
 PARSONS ENERGY AND CHEMICALS)
 GROUP, INC.; PRAXAIR, INC.; TEXACO)
 AVIATION PRODUCTS LLC; DAIKIN)
 INDUSTRIES, LTD.; SAINT-GOBAIN)
 PERFORMANCE PLASTICS; RIX)
 INDUSTRIES, INC.; TEXACO GLOBAL)
 GAS AND POWER; TEXACO)
 DEVELOPMENT CORPORATION;)
 GARY DELGREGO,)
)
)
 Defendants,)
)
 NORTHEAST CONTROLS, INC.,)
)
 Third-Party Plaintiff,)
)
 v.)
)
 CONECTIV OPERATING SYSTEMS,)
)
 Third-Party Defendant.)

DEPOSITION OF BHIM S. BHAKOO

WILCOX & FETZER
1330 King Street - Wilmington, Delaware 19801
(302) 655-0477



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COPY

1 Continued deposition of BHIM S. BHAKOO
2 taken pursuant to notice at the law offices of Saul
3 Ewing, LLP, 222 Delaware Avenue, Suite 1200,
4 Wilmington, Delaware, beginning at 9:35 a.m., on
5 Thursday, April 1, 2004, before Kurt A. Fetzer,
6 Registered Diplomate Reporter and Notary Public.
7

8 APPEARANCES:

9 JOSEPH HANDLON, ESQ.
10 ASHBY & GEDDES
11 222 Delaware Avenue
12 Wilmington, Delaware 19801
13 for the Plaintiffs

14 THOMAS P. WAGNER, ESQ.
15 RAWLE & HENDERSON LLP
16 The Widener Building
17 One South Penn Square
18 Philadelphia, Pennsylvania 19107
19 for the Third-Party Plaintiff and
20 Defendant Northeast Controls, Inc.

21 PAUL M. LUKOFF, ESQ.
22 PRICKETT JONES & ELLIOTT, P.A.
23 1310 King Street
24 Wilmington, Delaware 19801
25 for the Defendant Motiva Enterprises LLC

26 MICHAEL K. TIGHE, ESQ.
27 TIGHE COTTRELL & LOGAN, P.A.
28 First Federal Plaza
29 Wilmington, Delaware 19801
30 for the Defendant Battaglia Mechanical, Inc.

31 JAMES F. X. HILER, ESQ.
32 WECHSLER & COHEN, LLP
33 116 John Street - 33rd Floor
34 New York, New York 10038
35 for the Defendants Daikin Industries
36 and Daikin America

37

38

39



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41 Registered Professional Reporters

1 APPEARANCES: (Cont'd)

2 PHILIP T. EDWARDS, ESQ.
3 MURPHY SPADARO & LANDON
4 1011 Centre Road - Suite 210
Wilmington, Delaware 19805
for the Defendant HydroChem
Industrial Services, Inc.

5 R. STOKES NOLTE ESQ.
6 NOLTE BRODOWAY & SALTZ, P.A.
7 Three Mill Road - Suite 304
Wilmington, Delaware 19806
8 for the Third-Party Defendant
Conectiv Operating Systems

9 ALSO PRESENT:

10 PHILIP C. JACOBSON, REGIONAL GROUP COUNSEL
THE ST. PAUL PROPERTY AND LIABILITY INSURANCE

11 - - - - -

12 MR. McVEY: This will be the first
13 exhibit.

14 (Olson Deposition Exhibit No. 195 was
15 marked for identification.)

16 - - - - -

17 BHIM S. BHAKOO,
18 the deponent herein, having first been
19 duly sworn on oath, was examined and
20 testified as follows:

21 MR. RICHES: We will read and sign.

22 EXAMINATION

23 BY MR. McVEY:

24 Q. Good morning, Mr. Bhakoo.



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1 A. Good morning to you.

2 Q. I think we met back on December 11, 2003, did
3 we not?

4 A. I remember you very well.

5 Q. Okay. My name is Mr. McVey and I represent
6 Fisher Controls in this litigation.

7 A. How can I forget you?

8 Q. Okay. It's good to be known as memorable, I
9 guess.

10 Mr. Bhakoo, subsequent to December 11th
11 did you have an opportunity to read or review the
12 transcript of your deposition, the first portion of
13 your deposition that was taken back on December 11th?

14 A. Yes, I have.

15 Q. And did you make a number of additional changes
16 or did you make some changes to the transcript of that
17 deposition which you then signed off on on January 16,
18 2004?

19 A. That's correct.

20 Q. Since January 16, 2004, have you had occasion
21 to review this deposition again?

22 A. Since when?

23 Q. Since January 16, 2004, when you signed off on
24 the signature page, have you taken the opportunity to



1 specifications?

2 A. Yes.

3 MR. McVEY: Joe, could you turn to 31?

4 Q. Mr. Bhakoo, is Exhibit 31 the applicable
5 version of the EN-6 standard that you were referring
6 to in your testimony a minute ago?

7 A. It's close to that. The reason I am saying
8 that is it said the revision date is 6-15-98,
9 effective date is 6-25-98 and there were some
10 revisions to that, but the contents I think they are
11 close.

12 Q. When you say there were some revisions to that
13 standard, are you saying there's some revisions
14 after --

15 A. No. The valve was ordered on June 29th? Is
16 that the date? It would be in one here (indicating).

17 June 30th.

18 Q. Yes.

19 A. I issued the requisition on 6-26-98.

20 Q. Correct.

21 A. And so this document (indicating) was effective
22 6-25-98, so they are only one day apart.

23 So I will say this document (indicating)
24 is applicable because the previous version and this



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1 version there shouldn't be too much change.

2 Q. If you want to refer to the previous version,
3 sir, that's Exhibit 30.

4 A. Yes. This is the document which was in place.

5 Q. Up until 6-25-98?

6 A. Correct.

7 Q. Can you point to us the portion of EN-6 in
8 Exhibit 30, now that I have directed our attention to
9 that document, which would prohibit the use of Inconel
10 718 under these service conditions?

11 A. It is on page 13 of this, figure 3 and that's
12 where Inconel 718 is listed.

13 Q. And if we go to the service conditions here
14 which would be 99.7 percent oxygen, correct?

15 A. Correct.

16 Q. And then go up the pressure line to I guess
17 that we would be looking at 1300 as the max pressure
18 for this device?

19 A. Where is it at?

20 Q. On line 18. I'm going back to the
21 specification.

22 A. I don't have that. Is that this one here?

23 Q. That's in Exhibit --

24 A. 196?



1 Q. -- 196, Praxair 4271.

2 A. Okay. Which line again?

3 Q. Well, again, let me just ask you an open-ended
4 question.

5 In applying these service conditions to
6 the selection of materials, sir, which line would you
7 refer to?

8 A. I think we were talking about line No. 40.

9 Q. No. I understand, sir. But when I go to the
10 chart that's page 13 of 22 on Exhibit 30 and I'm
11 trying to apply the temperature and pressure
12 conditions, where do I go on Exhibit 4271, Praxair
13 document 4271?

14 A. Line 40.

15 Q. No. Where do I go for the pressure and
16 temperature conditions?

17 A. Pressure and temperature conditions? That's
18 line 3 and line 5.

19 Q. And my question to you, again, is a question
20 that when you're determining whether the stem material
21 can be Inconel or not Inconel, you have to take
22 temperature and pressure conditions from document 4271
23 and apply them to the graph that's on page 13 of
24 Exhibit 30. Is that correct?



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1 A. Are you suggesting that I physically did that?

2 Q. I'm just asking how this process works in
3 general. In order to determine whether Inconel is an
4 appropriate material or is consistent with Praxair
5 standards for this application, don't you have to look
6 at the temperature and pressure conditions?

7 A. Yes.

8 Q. For example, if the temperature and pressure
9 conditions here were 99.7 percent oxygen but you were
10 at 200 p.s.i.g., then Inconel 718 would fall into the
11 velocity exempt zone, correct?

12 A. Correct.

13 Q. And all I'm asking you is the question when I
14 take 4271 and I want to apply the process information
15 in this document, Praxair 4271, to page 13 of Exhibit
16 30, where do I take the pressure and temperature
17 conditions from?

18 A. From line 3 under the maximum column. The
19 pressure is 1167 and temperature is 100 and the
20 shutoff column the pressure is 1300.

21 Q. And in doing this would you take the higher of
22 those two?

23 A. Correct.

24 Q. And so if we take 1300 p.s.i.g. at 99.7 percent



1 oxygen on page 13 out of 22 on Exhibit 30, we find
2 that Inconel is in the non-exempt zone?

3 A. Correct.

4 Q. And that's the inconsistency with the Praxair
5 EN-6 standard that you determined existed following
6 Mr. Olson's accident with respect to the 613 valve?

7 MR. RICHES: I'll object to the form.

8 You can answer.

9 A. That is correct.

10 Q. Are you aware of a material, sir, that could be
11 used for the stem material of the 613 valve where you
12 could just change the stem material and have this
13 valve be consistent with Praxair standards that would
14 work in this service condition?

15 A. Looking at the EN-6, there are so many other
16 materials listed in this on page 8. If it was Inconel
17 117, that is good up to 1400 pounds. And if it is
18 Inconel 117 instead of Inconel 718, that will be fine.

19 And that's not the only one. There are
20 many others.

21 Q. Okay. So we can go back to page 8 of 22 of
22 Exhibit 30 and we can find other materials that we
23 could use for the stem material that would meet
24 Praxair's internal standards?

1 State of Delaware)
2)
New Castle County)

3

4 CERTIFICATE OF REPORTER

5
6 I, Kurt A. Fetzer, Registered Diplomate
7 Reporter and Notary Public, do hereby certify that
there came before me on the 1st day of April, 2004,
the deponent herein, BHIM S. BHAKOO, who was duly
sworn by me and thereafter examined by counsel for the
respective parties; that the questions asked of said
deponent and the answers given were taken down by me
in Stenotype notes and thereafter transcribed by use
of computer-aided transcription and computer printer
under my direction.

11 I further certify that the foregoing is a true
12 and correct transcript of the testimony given at said
examination of said witness.

13 I further certify that I am not counsel,
attorney, or relative of either party, or otherwise
interested in the event of this suit.

15
16 
17 Kurt A. Fetzer, RDR, CRR
18 Certification No. 100-RPR
(Expires January 31, 2005)

19

DATED:

4-6-04

20

21

22

23

24



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Registered Professional Reporters

EXHIBIT 69



In the Matter Of:

**Northeast Controls Inc. and St. Paul
Mercury Insurance**

v.

Fisher Controls International, LLC

C.A. # 06-412

Transcript of:

**Bhim S. Bhako
Volume # 3
October 16, 2007**

IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

NORTHEAST CONTROLS, INC.,)
ST. PAUL MERCURY INSURANCE)
COMPANY,)
)
Plaintiffs,	) Civil Action
	) Number 06-412
v.)
)
FISHER CONTROLS	) Volume III
INTERNATIONAL, LLC,	) Pages 385 - 447
)
Defendant.)

Deposition of BHIM S. BHAKOO, taken pursuant to notice at the law offices of Cozen & O'Connor, 1900 Market Street, 4th Floor, Philadelphia, Pennsylvania, beginning at 10:33 a.m., on Tuesday, October 16, 2007, before Julie H. Parrack, Registered Merit Reporter, Certified Realtime Reporter and Notary Public.

APPEARANCES:

THOMAS P. WAGNER, ESQUIRE
MARSHALL DENNEHEY WARNER COLEMAN & GOGGIN
1845 Walnut Street
Philadelphia, Pennsylvania 19103
On behalf of Plaintiffs

DANIEL J. GUNTER, ESQUIRE
RIDDELL WILLIAMS P.S.
1001 Fourth Avenue Plaza, Suite 4500
Seattle, Washington 98154-1065
On behalf of Defendant

ALSO PRESENT: JOSEPH RICHES, ESQUIRE
COZEN & O'CONNOR
On behalf of Bihm S. Bahkoo

WILCOX & FETZER
1330 King Street - Wilmington, Delaware 19801
(302) 655-0477
www.wilfet.com

FCI/MSJ 0843

1 A. Correct.

2 Q. I want to ask a few questions. Did you, when
3 you were specifying the 629 valve on behalf of
4 Praxair, have a mutual agreement with Northeast
5 Controls that the disk of the 629 valve was to be
6 manufactured of Hastelloy C?

7 A. No.

8 Q. Again, when you were specifying the 629 valve,
9 did you have a mutual agreement with Northeast
10 Controls that the stem of the 629 valve was to be
11 manufactured of Inconel 718?

12 A. No.

13 Q. When you were specifying the 629 valve on
14 behalf of Praxair, did you have a mutual agreement
15 with Northeast Controls that the guide material for
16 the 629 valve would be TFE composite?

17 A. No.

18 Q. Did you, when you were specifying the 629 valve
19 on behalf of Praxair, have a mutual agreement with
20 Northeast Controls that the seat of the 629 valve was
21 to be manufactured by Tefzel?

22 A. No.

23 Q. Did you, when you were specifying the 629 valve
24 on behalf of Praxair, have a mutual agreement with

1 Northeast Controls that the seat of the 629 valve was
2 to be manufactured of Kel-F?

3 A. No.

4 Q. And is Kel-F also known as Neoflo 400?

5 A. Yes.

6 Q. In ordering the 629 valve, did you deal with
7 anyone who was an employee of Fisher Controls
8 International, Inc., to the best of your knowledge?

9 A. No.

10 Q. Did you deal with anyone in ordering the 629
11 valve who was not an employee of Northeast Controls,
12 Inc., to the best of your knowledge?

13 A. No.

14 Q. Taking some time, you answered some of the
15 questions I have already, and so I wanted to make sure
16 that I'm not just formally going through my...

17 Just a few more questions, to go back on
18 those and I think I'm done.

19 Would it have been acceptable to you for
20 Northeast Controls or Fisher to change the material of
21 the disk from Monel to Hastelloy C without obtaining
22 Praxair approval?

23 A. No.

24 Q. Would it have been acceptable to you for

1 Northeast Controls or Fisher to change the material
2 for the stem from Monel to Inconel 718 without
3 obtaining Praxair approval?

4 A. No.

5 Q. Would it have been acceptable to you for
6 Northeast Controls or Fisher to change the material
7 for the seal from Monel/PTFE to Tefzel without
8 obtaining Praxair approval?

9 A. No.

10 Q. Would it have been acceptable to you for
11 Northeast Controls or Fisher to change the material
12 for the seal from Monel/PTFE to Kel-F without
13 obtaining approval?

14 A. No.

15 Q. Would it have been acceptable to you for
16 Northeast Controls or Fisher to change the guide for
17 bearing material from Monel to TFE composite without
18 obtaining Praxair approval?

19 A. No.

20 Q. 356, this is in the Exhibit 18, if we look at,
21 starting at line 2, on 356, there's a line there:

22 "QUESTION: And then do you ultimately
23 make the determination about the metallurgy or is that
24 something you do in conjunction with the manufacturer?

1 "MR. RICHES: I'll object to form."

2 MR. RICHES: And you can see why, can't
3 you? It's a compound question.

4 Q. "You can answer." And then you stated, "I have
5 the final say in terms of metallurgy because when it
6 comes to safety, Praxair safety requirements must be
7 met."

8 And let me just ask the question without
9 the compound form, first, do you or at that time did
10 Praxair ultimately make the determination about
11 metallurgy for control valves?

12 A. Correct.

13 Q. I think that was -- let me try that one again.

14 Did Praxair ultimately make the
15 determination about the metallurgy in the control
16 valves? That's a yes, was that a yes earlier?

17 A. Yes.

18 Q. Okay. I phrased it a little bit differently,
19 so "correct" was maybe not the best answer.

20 And then you go on to answer here, you
21 say, "I have the final say in terms of metallurgy
22 because when it comes to safety, Praxair's safety
23 requirements must be met. I can listen to the
24 vendors. They have their own experience. If I don't

1 like it, I will insist on changing the material to
2 what we want." Right?

3 A. Yes.

4 Q. And there was no inquiry to you from -- or let
5 me ask you. Was there an inquiry to you from
6 Northeast Controls or Fisher after June 3, 1998
7 whether to change the disk from Monel to Hastelloy C?

8 A. No.

9 Q. Same question: Any inquiry as to changing the
10 stem from Monel to Inconel 718?

11 A. No.

12 Q. Same inquiry, or same period of time, et
13 cetera: Any inquiry from Northeast Controls or Fisher
14 as to changing the seat material from Monel/PTFE to
15 Tefzel?

16 A. No.

17 Q. Same period of time: Any inquiry from
18 Northeast Controls or Fisher as to changing the seat
19 material from Monel/PTFE to Kel-F?

20 A. No.

21 Q. And same period of time: Any inquiry from
22 Northeast Controls or Fisher as to changing the guide
23 or bearing material from Monel to TFE composite?

24 A. No.

1 CERTIFICATE

2 STATE OF DELAWARE)

3)

4 NEW CASTLE COUNTY)

5 CERTIFICATE OF REPORTER

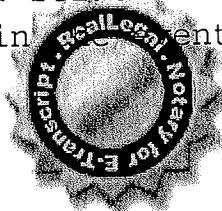
6 I, Julie H. Parrack, Registered Professional
7 Reporter and Notary Public, do hereby certify that
8 there came before me on the 16th day of October, 2007,
9 the deponent herein, BHIM S. BHAKOO, who was duly
sworn by me and thereafter examined by counsel for the
respective parties; that the questions asked of said
deponent and the answers given were taken down by me
in Stenotype notes and thereafter transcribed by use
of computer-aided transcription and computer printer
under my direction.

10

11 I further certify that the foregoing is a true
12 and correct transcript of the testimony given at said
examination of said witness.

13

14 I further certify that I am not counsel,
15 attorney, or relative of either party, or otherwise
interested in the outcome of this suit



Julie H. Parrack

16 Julie H. Parrack, RMR, CRR
17 Certification No. 102-RPR
18 (Expires January 31, 2008)

19

20

21

22

23

24

DATED: _____

CERTIFICATE OF SERVICE

I, Paul A. Bradley, Esquire, hereby certify that, on November 29, 2007, I caused a true and correct copy of the following documents to be served upon counsel of record via electronic filing and hand delivery:

1. Defendant Fisher Controls International, LLC's Reply Brief in Support of its Motion for Summary Judgment; and
2. Affidavit of Daniel J. Gunter in Support of Defendant Fisher Controls International, LLC's Reply Brief in Support of its Motion for Summary Judgment.

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/s/ Paul A. Bradley

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